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Phase change material in automated window shades

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Date: June 10, 2013

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION
BY

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ENTITLED

PHASE CHANGE MATERIAL IN AUTOMATED WINDOW SHADES

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

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THESIS

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Abstract

The purpose of this report is to detail the development process for a phase change material window shading system, which stores solar thermal energy and later releases it indoors to provide nighttime space heating. To do this, wax-filled louvers with thermally absorptive front faces were developed and outfitted with a control system, which utilized historical weather data to orient the louvers to specific solar azimuthal angles, thus maximizing the thermal absorption. The system was tested against other common window treatments in a pair of thermally comparable testing structures, and was found to provide energy savings as high as 50%.

Acknowledgements

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Table of Contents

Chapter 1: Introduction

Section 1.1: Background/Motivation

The average California household uses 6,800 kWh of electricity and 38 million BTUs of natural gas each year,[1, 2] equating to a $1700 annual utility bill.[3] Natural gas and coal resources continue to decrease, while the amount of energy consumed by Americans continues to increase. Today, there is a continuous effort to create energy efficient appliances, to aid in daily reduction of energy consumption. In particular, HVAC (Heating, Ventilation and Air Conditioning) systems account for approximately 55% of the energy consumed in residences throughout the United States[4], in comparison to other appliances (as shown in Figure 1). Heating and cooling systems are now considered a home necessity, so eliminating the need for space heating would decrease utility costs and preserve natural resources.

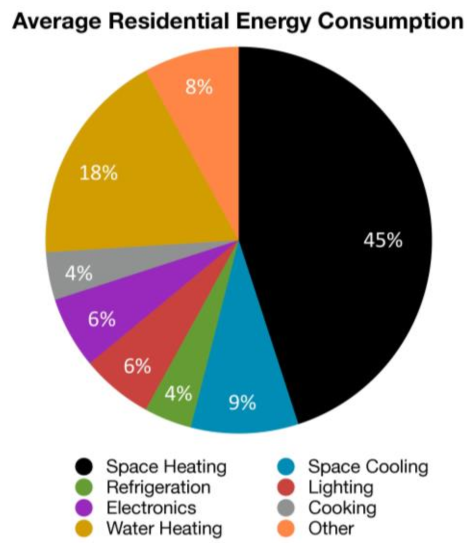

Figure 1: Percentage of energy used by appliances in the average United States household.[4]

All homes have windows, but windows account for an average of 20% of the heat loss and gain in a home.[5] Window coverings have not changed substantially since their invention. But what if a window shade could do more than just block the sun? What if it was intelligent, and actively made your living space more comfortable and sustainable? Our objective is to develop a window shade product that emits heat into a domestic household, with little consumption of an alternate energy source to operate. In order to achieve this goal we must optimize technology that absorbs and

[1]"California QuickFacts from the US Census Bureau." State and County QuickFacts. N.p., n.d. Web. 8 February 2013. http://quickfacts.census.gov/qfd/states/06000.html.

[2] Clean Energy in My State: California Residential Energy Consumption." U.S. DOE Energy Efficiency and Renewable Energy (EERE) Home Page. N.p., n.d. Web. 8 February 2013. http://apps1.eere.energy.gov/states/residential.cfm/state=CA#elec

[3] "Rates & Tariffs Library." *Pacific Gas and Electric Company*. N.p., n.d. Web. 8 Feb. 2013. <http://www.pge.com/en/about/rates/index.page>.

[4] Tips: Your Home's Energy Use | Department of Energy." Energy.gov | Department of Energy. N.p., n.d. Web. 4 May 2013. <http://energy.gov/energysaver/articles/tips-your-homes-energy-use>.

[5] Katz, Arnie. "Advanced Energy."*Advanced Energy, an Energy Efficiency Services Firm*. N.p., n.d. Web. 8 Feb. 2013. <http://www.advancedenergy.org/building

stores energy, but also functions as a home furnishing purchased by the average homeowner. Installing an energy efficient window treatment would make this possible, and allow a substantial amount of money to be recovered from energy that would have otherwise been lost to the environment through a window.

Section 1.2: Technical Objective

In order to solve this problem of environmental heat loss, our team proposed to develop Phase Change Material (PCM)-filled crescent-shaped louvers to replace traditional window blinds. The window shading system could be installed indoors, behind a window. A cross-section of the basic louver prototype is shown in Figure 2. One key phase of the project was deciding which material to use for each aspect of the design. The flat side of the louver was made of a highly emissive material to effectively absorb and release solar energy. A black body, or material that can ideally absorb all electromagnetic radiation obtained from natural sunlight, had potential to be used as the flat, conductive surface—graphite-coated glass and acrylic were the two most reliable options. The semi-circular back-edge of the louver was ideal to be comprised of a reflective and insulating surface to avoid heat loss through this specific material. During the day, the flat side of the blind faces outwards, keeping the interior cool. The heat from the sun melts the enclosed PCM, yet does not permeate through the blind into the room because of the reflective, insulating surface. During the night, the blinds flip so the flat edges face inside and release the latent heat indoors. The PCM selected for utilization in the system design was chosen based on how low its melting temperature is. The proposed crescent louver design was optimized so that each blind had a large conductive surface to absorb large quantities of sunlight, as well as a thick reflective surface for high quantities of paraffin wax to be stored. The louvers also were intended to be aesthetically pleasing while maintaining relatively cheap material costs.

The design also consists of a control system that operates the blinds so that they switch position throughout the day, depending on the temperature, and brightness of the sun. Upon detection of a significant drop in the ambient temperature and light, the louvers automatically flip inward, thus beginning the solidification of the wax and the heating of the house; this incorporates the use of temperature, brightness, and motion sensors. The three sensors were programmed to work together to ensure that the available thermal energy was used to space heat the house in the most efficient manner.

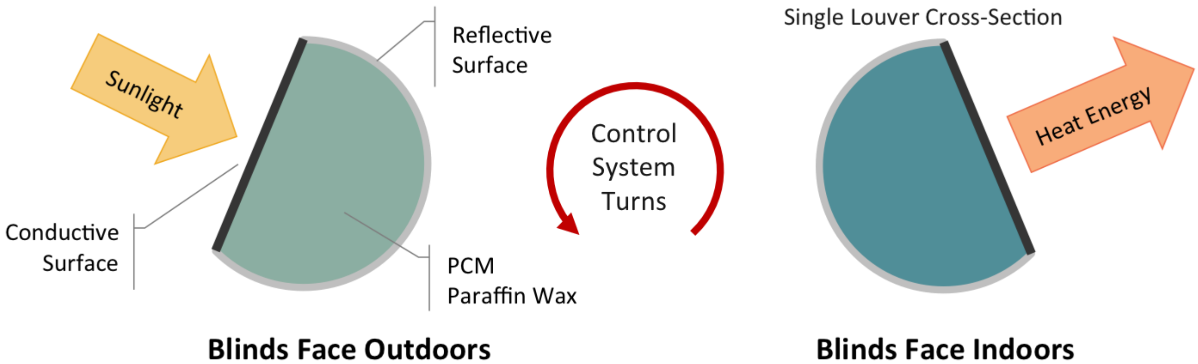

Figure 2: Side view of the rotating louvers with heat absorption during the day and emission at night, in order to replace nighttime space heating. Three key innovations in our design include: the louver Surface Finish, Phase Change Material, and Control System that make our product unique to other inventions.

Section 1.3: Review of Field Literature

Mohammed Farid's *A Review on Phase Change Energy Storage: Materials and Applications* propelled our decision to make use of phase change material as a solution to the thermal energy usage issue. He summarizes that PCMs' utilization of latent heat storage is one of the most efficient ways of storing thermal energy. Latent heat storage differs from sensible heat storage in that it utilizes phase change to store energy with greater density and with a smaller range of temperature needed between the storage and the release of heat. Much research has been done on a wide variety of PCMs, including different material types with various melting and solidifying temperatures. These various types of PCMs include paraffin wax, which has moderate thermal energy storage, but a low thermal conductivity requiring a large surface area to heat, and hydrated salts, which have a larger energy storage density and higher thermal conductivity but are prone to super-cooling and phase separation[6]. Paraffin wax is a common and cheap option for a PCM that has been developed with various melting and solidifying temperatures in ranges, making them attractive for commercial and residential thermal storage and temperature control. Farid concludes that the main advantage is PCM encapsulation, a technique that makes use of the PCM by placing the material in a storage unit. He states that encapsulation of PCMs can increase heat transfer area, control the changes in volume, and protect the heat transfer fluid from the outside environment. The two types of encapsulation include: Macro- and Micro- encapsulation, macro- being storage of PCMs in large

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[6] Farid, Mohammed, Amar Khudhair, Siddique Razack, and Said Al-Hallaj. "A Review On Phase Change Energy Storage: Materials And Applications."*Energy Conversion and Management*45.9-10 (2004): 1597-1615. Print.

volume containers and micro- in small volume containers. Previous studies have shown that paraffin's and salts had a tendency to solidify at the edges of macro-containers, which makes micro-encapsulation and optimization of the storage unit favorable.[7] These conclusions lead to our decision to make individual louvers, rather than a huge mass in front of a window, as well as design the size of each individual blind by increasing the available energy as much as possible while increasing the surface area to mass ratio.

Atul Sharma's *Review on Thermal Energy Storage with Phase Change Materials and Applications* aided in identifying current thermal storage applications developed, which include heat pumps, solar engineering, and spacecraft thermal control[8]. He indicated that over the past decade, engineers have experimented with PCMs for heating and cooling applications in buildings, but he did not mention use of PCMs in windows, which reconfirms the uniqueness of our product. The realization in the literature that there are many varieties of PCMs with different melting and solidifying temperatures, deduces that they are optimum for use in varying environments as well. Recently, PCMs have also been applied to heating and cooling buildings. Amar Khudhair's *A review on energy conservation in building applications with thermal storage by latent heat using phase change materials* summarizes that Using PCM encapsulated in walls, ceilings and floors capture solar radiation and create smaller temperature variations and maintain desired temperatures for longer periods of times, and is similar to our proposed product. Research in building applications include: PCM encapsulated in concrete, gypsum wallboard, ceiling and floor, and have shown promising results resulting in a successful improvement in building heating.[9]

Frédéric Kuznik's E*xperimental Assessment of a Phase Change Material for Wall Building Use* documented full scale tests conducted to evaluate the performance of a PCM copolymer composite wallboard in a controlled environment. The results proved successful use of PCMs for the opposite effect we hope to achieve, by lowering the temperature in a room during a hot day by 4.2° C and enhancement of the natural convection into the room.[10] However, using PCMs in building materials

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[7] Ibid, Farid.

[8] Sharma, Atul, V.V. Tyagi, C.R. Chen, and D. Buddhi. "Review On Thermal Energy Storage With Phase Change Materials And Applications." *Renewable and Sustainable Energy Reviews* 13.2 (2009): 318-345. Print.

[9] Khudhair, Amar, and Mohammed Farid. "A Review On Energy Conservation In Building Applications With Thermal Storage By Latent Heat Using Phase Change Materials." *Energy Conversion and Management* 45.2 (2004): 263-275. Print.

[10] Kuznik, Frédéric, and Joseph Virgone. "Experimental Assessment Of A Phase Change Material For Wall Building Use."*Applied Energy* 86.10 (2009): 2038-2046. Print.

such as walls and floors have not allowed for consistent and precise control of the release of energy. Also, current thermal energy storage (TES) technologies have primarily been developed to use PCMs either as simple thermal mass such as the wallboard, or in complicated systems in which the PCM is pumped through the structure. In each case, the final result has suffered from an excessive ambient heat loss, or required an unrealistic amount of pumping power. [11,12,13] Our system utilizes a simple control system to maximize energy storage and minimize energy wasted in losses and the actuation and control system, to combat the issues found in recent PCM studies.

[11] Ibid, Farid.

[12] Ibid, Sharma.

[13] Ibid,

Chapter 2: Initial Design Process and Evaluation

Section 2.1: Customer Needs Assessment and User Scenarios

Our team conducted a customer needs and market research report targeting potential end-users and buyers of the product. Our final system is being integrated into Kennedy Commons, a highly sustainable building on Santa Clara University's campus. As such, the primary end-user of our project will be the students and faculty. Originally our product was going to be used in the Santa Clara University Solar Decathlon Radiant House, so we initially added SCU's 2013 Solar Decathlon Interior Design Team as a potential end-user. The Interior Design team is ultimately responsible for the products and materials that will be put into the Radiant House and provided input on how our product could have been integrated into the bedroom's aesthetics. Our goal of marketing design, or at least providing a marketable design meant that we also had to think about the customers that would potentially be purchasing our product. Since our project focused on using solar energy and diminishing the need for electricity or gas heating, our marketing strategy was directed towards customers who are interested in a "green" home and saving large amounts of energy. These potential customers include but are not limited to solar homeowners, corporate business parks, apartment complexes, and even the average California homeowner. When examining the potential social impact in underdeveloped regions, we specifically targeted North Africa where our product could be utilized due to its hot days and cold nights.

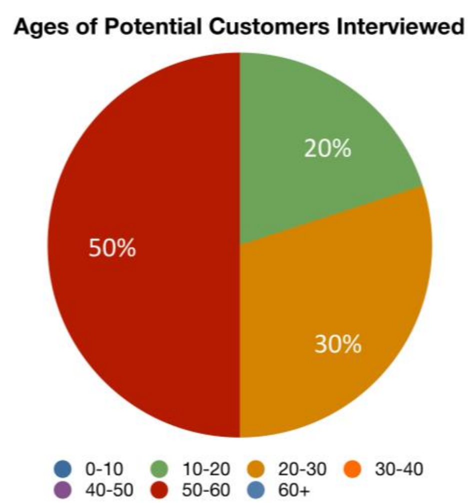

Figure 3: Age demographics of potential customers interviewed in CNA Report.

The Customer Needs Assessment (CNA) provided our team with valuable information during the design process of our product. Though we were not able to cover all of the demographics, we were able to acquire a large amount of information which spurred the development of ideas beyond our original design. The individuals interviewed and the demographic that each of them represented were the most important audiences that we will market our product to. Table 1 and Figure 3 show the demographics of those that were interviewed or took our survey, with the largest input coming from middle-aged female homeowners. Further detail including the questions asked and responses are included in Appendix A.4.

Table 1: Gender and home-ownership demographics of potential customers interviewed in CNA Report.

Gender		Homeowners	
Female	Male	Yes	No
6	4	6	4

After conducting the CNA, we established that the best input came from interviewing potential customers, rather than conducting a written survey. Discussing the product with the user and being able to answer questions brought about many concerns that our team did not take into consideration at the initial phase of our product. Though we targeted our primary audience, female homeowners, in this assessment, it would have been useful to receive input from more males, apartment residents, and managers of business parks and corporation buildings, since they could also be a high-volume market. Unfortunately, we did not receive enough valid data from corporate managers working in a business park setting to come to any conclusions, but we foresee that becoming a very large and profitable market. After receiving little information from the questionnaire, another customer was interviewed briefly on the potential for the corporate market. Having direct input from an outside point of view revealed that our blind system would be best suited for, and most accepted in only select areas of a building that would require nighttime heating. Many of the rooms within each building do not have bodies or materials in those rooms that need to stay warm throughout the night. A manufacturing floor (non-clean room setting), call-centers, and security office would be optimum, but it may not be beneficial in office areas where light is necessary in order to keep employees awake and motivated. Those employees often don't stay late or long enough to require nighttime heating from sunset to sunrise. The feedback from this customer field has also led our group to the conclusion that we should investigate other potentially high profit markets.

Many of the interviewed individuals provided responses outside of the questionnaire, which made our team realize that we needed to further establish the scope of our project at that time. Our initial design was to have a built-in system, but that was a major disadvantage based on all of the feedback. One interviewee recommended that the blinds have the ability to be stowed during the day if natural daylight was desired, or that they be developed for installation in a skylight. What was also established from interviewing homeowners was that many of them are only home during the day on weekends. This confirms that users are not willing to manually adjust blinds during the day to cut the cost of the blinds and increase the amount of heat to your room and would prefer and be willing to pay for an automatic system. This also confirms that the stow away feature would only be used on weekends and is not that large of a priority for our senior design project, but will be taken into consideration for future manufacturing. The customer needs were organized into groups and hierarchies, as shown in Table 2. Based on the data collected and discussion of the Product Design Specification (PDS) found in Appendix A.1, it was established that we had to place higher attention on keeping the product safe, low cost, aesthetically pleasing, low maintenance, and easy to set-up.

Table 2: Hierarchy of customer needs identified based on team's evaluation of priority.

Priority	Specification	Specifics
1	Safety & Legal	Ensure each component of the device is safe for any body that many interact with it. (Not-toxic, sharp edges, fire hazard, short circuits, etc.)
2	Price	Keep the price as low as possible, and below $100 overall.
3	Cost	Keep the manufacturing cost lower than the price of the product.
4	Usability	Ensure the user operation of the system is easy to use and basic. Minimize the amount of buttons and ideally have one On/Off switch.
5	Shelf Life	Ensure the product, particularly the PCM core, has a long shelf life of at least 5 years so that the customer will purchase as an investment product.
6	Aesthetics	Design product with sleek, natural materials and minimize the size and bulkiness of the louvers and control system.
7	Set-Up	Provide product as build-up as possible to make an easy and short set-up for the customer. Do not let the installation exceed 1 hour.
8	Maintenance	Choose materials that do not require regular cleaning and a control system energy source that lasts at least 2+ years.
9	Size	Make the system as small and sleek as possible, to blend in the room.
10	Weight	Minimize louver weight for less required energy and installation.
11	Design	Ensure the louver and control system work harmoniously.
12	Quality & Testing	Ensure we have a product that is of the highest quality, safe, and operates correctly with documented and effective testing.
13	Eco-Friendly	Choose materials that are non-toxic to the environment, in high volume, and preferably sustainable and biodegradable.
14	Competition	Constantly compare and design our product so that it has more appealing features and improvements in every aspect of the competition.
15	Patents	Search for patents to establish if any component of our product is patentable and will provide us with a leg-up to the competition.
16	Disposal	We would like an environmentally conscious product, so ensure all materials are non-toxic, preferably biodegradable, and easily disputable so they can be placed in residential garbage or recycling bin at end-of-life.
17	Manufacturing Process	Minimize steps and cycle times to ensure a quick, but high quality manufacturing of product.
18	Documentation	Documentation of Product Development and all future endeavors.
19	Packaging	Minimize the amount of packaging used to limit the amount of environmental resources used, but ensure the product will safely arrive to the customer.
20	Shipping	Minimize packaging but take load impacts into consideration so that the product does not break in cargo.

Safety is a high priority in any system with which people and pets interact. Our team established that safety was the top priority within the hierarchy of our design and analyzed particular component concerns and mitigations in Chapter 7, Engineering Standards and Realistic Constraints.

When selling a product to the average homeowner, it must be understood that the buyer will not want to spend great amounts of time and brainpower assembling and installing the product. Therefore the mass production of the blind system will require shipment of the system as mostly assembled, easily recognizable parts, and a clear assembly manual. All of our potential users were obviously not in favor of a long and strenuous set-up, or the idea of paying a hefty fee to an installation service. We attempted to make the control set up as clear and easy as possible, without a need for tuning.

Everyone who was interviewed had some issues with the price that was proposed for this particular louver design. Most younger interviewees, less than 30 years of age, claimed to want to spend no more than $500 on a total set; comparatively, most homeowners had a maximum dollar value of $200. The final prototype cost was exceedingly high for the final assembly, mostly due to shipping costs for the PCM and the control system components. A benchmark was performed, analyzed in Chapter 2.3, to establish a mass production price goal of $800. During the mass production phase, the manufacturing cost must be kept lower than the price of the product, and we hope to do that by seeking out local PCM providers, and purchasing and manufacturing components in larger quantities.

Many customers had concerns about how long the louver system would last. It does not make sense to make this investment, realistically, if the cost of implementation exceeded the financial savings in energy that these louvers would provide. Paraffin wax, the Phase Change Material that will be implemented into the finished product, has an estimated lifespan of 20,000 cycles[14], approximately 54 years. The limiting factor with the blind system seems to be the control system, which will fatigue with usage. The gearing system will be made out of hardened steel, which has been heat treated to withstand large amounts of friction and torque,[15] to provide a minimum of 20 years of use.

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[14] Rubitherm Technologies GmbH. Sperenberger Str. 5a, D-12277 Berlin. 49 30 720 004 62. Potential source for Phase Change Material.

[15] Ulrich, Karl T., and Steven D. Eppinger. Product design and development. New York: McGraw-Hill, 1995.

We initially determined that our target demographic would be homeowners, preferable with solar installed on their homes, because they would be interested in an environmentally friendly product that would save them money. The consensus was that they would like blinds that come in a variety of colors, but particularly natural colors and textures similar to those they currently have in their home. We used this feedback to design our current control system and blinds so that they are sleek and modern. Potential users had concerns that the system would be too bulky and would draw attention away from other items in the room, so the size of the system was reduced as much as possible to address that apprehension. After set-up, customers wanted a user-friendly system that was easy to understand and control. Our current system will need further aesthetical design, as well as minimization of controls. Ideally it will have one on/off switch, for the mass production stage. For the current final prototype we wanted to confirm that the product worked as intended before spending too much of the design process working on aesthetics and usability.

Section 2.2: Existing Products and Improvement

In order to design a blind system that appealed to customer needs, similar products were analyzed as potential competitors. The strengths and weaknesses of each were taken into consideration to determine which features were most important to incorporate in our design. Most importantly, we examined the thermal characteristics of each product by comparing insulating resistances, referred to as R-values. A low R-value results in significant heat loss, whereas a high R-value has less heat loss. Each of the compared window and blind system is summarized in Table 3. As shown, a standard set-up with a single-pane window and typical linen pleat blind is the most inexpensive option, but also the least insulative, increasing utility costs. Cellular shades are the most similar product on the market to our proposed design with a high thermal resistance, but are extremely expensive and do not emit heat energy. Our design has an insulated crescent back, and when combined with a double-pane window will has a minimum R-value of approximately 6.8. Though this is fairly high, if more insulation is needed for colder climates, silica aerogel can be added to increase the R-value to 10. Theoretically, our blind system will emit 2.526 kWh of heat energy for a 3-foot by 7-foot window, a feature that none of the other blind systems has. During the mass production stage, if we are able to keep the cost and price of our system below $800, while taking aesthetics into consideration, we could potentially have the best product on the market.

Table 3: Benchmark comparing competing systems with the PCM Automated blind system.

Product[16]		Cost *	Heat Loss (R-Value[17])	Comparison
	Single-Pane Window + Standard Linen Pleat Blinds	$200	Maximum Heat Loss (3.2)	Provides very little insulation, and no heat production. Most inexpensive, but least effective.
	Double-Pane Window + Wood Blinds	$350	Median Heat Loss (4.0)	Provides more insulation, but no heat production. More expensive, with moderate effectiveness.
	Double-Pane Window + Cellular Motorized Shades	$850[18]	Minimum Heat Loss (6.6)	Retracts up and down with remote, and the cellular material prevents light and heat transfer from filtering through when closed. Good insulation, but no heat production and expensive.
Phase Change Material in Automated Window Shades		<$800	Heat Source (6.8)[19]	Provides the best insulation and emits 2.526 kWh of heat energy for a 3' x 7' window. Includes a potentially less expensive motorized control system.

* Cost is for a 3-foot by 7-foot window and does not include installation and window cost.

[16] "Custom Window Treatments - Modern Drapes, Window Shades, Fabric Blinds, Silk Drapery & Contemporary Curtains | The Shade Store." Custom Window Treatments - Modern Drapes, Window Shades, Fabric Blinds, Silk Drapery & Contemporary Curtains | The Shade Store. http://www.theshadestore.com/ (accessed November 10, 2012).

[17] "Next Day Blinds: Energy Efficient Window Treatments." Next Day Blinds | Shades, Blinds, & Shutters. http://www.nextdayblinds.com/energysavers.asp (accessed November 19, 2012).

[18] "Menards - 500." Menards - Dedicated to Service & Quality™. http://www.menards.com/main/skusummary.html?cid=9239&sid=1857595&pid=1857536 (accessed November 10, 2012).

[19] "R-value (insulation) - Wikipedia, the free encyclopedia." *Wikipedia, the free encyclopedia*. N.p., n.d. Web. 19 Nov. 2012. <http://en.wikipedia.org/wiki/R-value_(insulation)>.

Section 2.3: Functional Analysis and System Level Requirements

The overall system consists of three main sub-systems including: the Louvers, Control and Actuation System, and Phase Change Material. Each sub-system plays an integral part in the overall function of the system. The initial goal of the overall system was to have an integrated and functioning device, which was met in our final prototype. This was done with optimization of the louvers for energy absorption and storage, so that the PCM will melt and solidify completely. The louver's shape was optimized to hold the highest amount of PCM without impeding the phase change process. We also chose and tested several varieties of PCM to determine the paraffin wax with a melting temperature and heat capacity favorable for Santa Clara's environmental conditions. The control system has the ability to follow the sun throughout the day and orient the blackbody surface of each louver in that direction via historical data of solar azimuthal angles. Depending on the seasonal sunset, the control system rotates all louvers simultaneously – without interactions with each other – towards the inside of the house when the temperature drops. One constraint the control system has in comparison to other windows is allowing this simultaneous movement while covering and shading the surface area of the window completely.

The key system level issues are almost all dependent on the requirements and potential constraints outlined for each sub-system. Initially, the major concern of operation for the entire system was the functionality of each sub-system as a unit. Fortunately, the design took this into consideration and our team worked hand-in-hand when manufacturing the louvers and control system so that the integration of the two resulted in functionality, but only covered about 90% of the window. The analysis of PCM was primarily dependent on the available volume in the louvers and control system's weight capacity. So the design process started with the design of the louvers, particularly the size, then the analysis and choice for the paraffin wax, and finally the control system, which was designed to function within the constraints imposed by the previous two completed sub-system designs. The next step during the mass production phase will be to look into optimizing the manufacturing process, since prototype manufacturing introduced changes into the design of the system, and took considerably more time and effort than was expected.

In order to analyze the functionality of our system, a layout drawing was created to provide a geometric interpretation of the major sub-systems, functional groups and potential risks. Figure 4 identifies the sub-components of the system as the louver, phase change material, and control system. The additional functions include the black body and reflective surface, solar and alternate energy sources. Potential risks for each item are classified with the blue dotted lines. As shown, a potential risk in regards to absorbing and emitting solar energy is cloud coverage, which in turn introduces the risk of our product, particularly the blackbody surface not working as intended since it would be unable to absorb enough energy to completely melt the phase change material. This then leads us to potential risks involved with the phase change material and it's interaction with the louver. The PCM has a 10% expansion rate during the phase change process, which could lead to high pressures at the bottom of the louver if the louver is sealed, possibly leading to the failure of the water-tight seal. Alternatively, it could lead to PCM leakage from one or more access holes at the top of the louver when the PCM is in a full liquid state. The back, reflective surface of the louver has to prevent heat transfer during the day and night to keep the room cool and warm at various times of the day, but if it is not insulated well enough there could be potential heat loss, which would decrease performance of the system. Finally, the control system could potentially cause the failure of one or more of the louvers if it causes vibration or doesn't allow the set to rotate easily and simultaneously. The control system could harm the operation and benefits involved with our system if there is sensor lag, or the energy source consumes more energy than the system emits. Mitigations to all of these potential risks were established in the iterative design process of each sub-system.

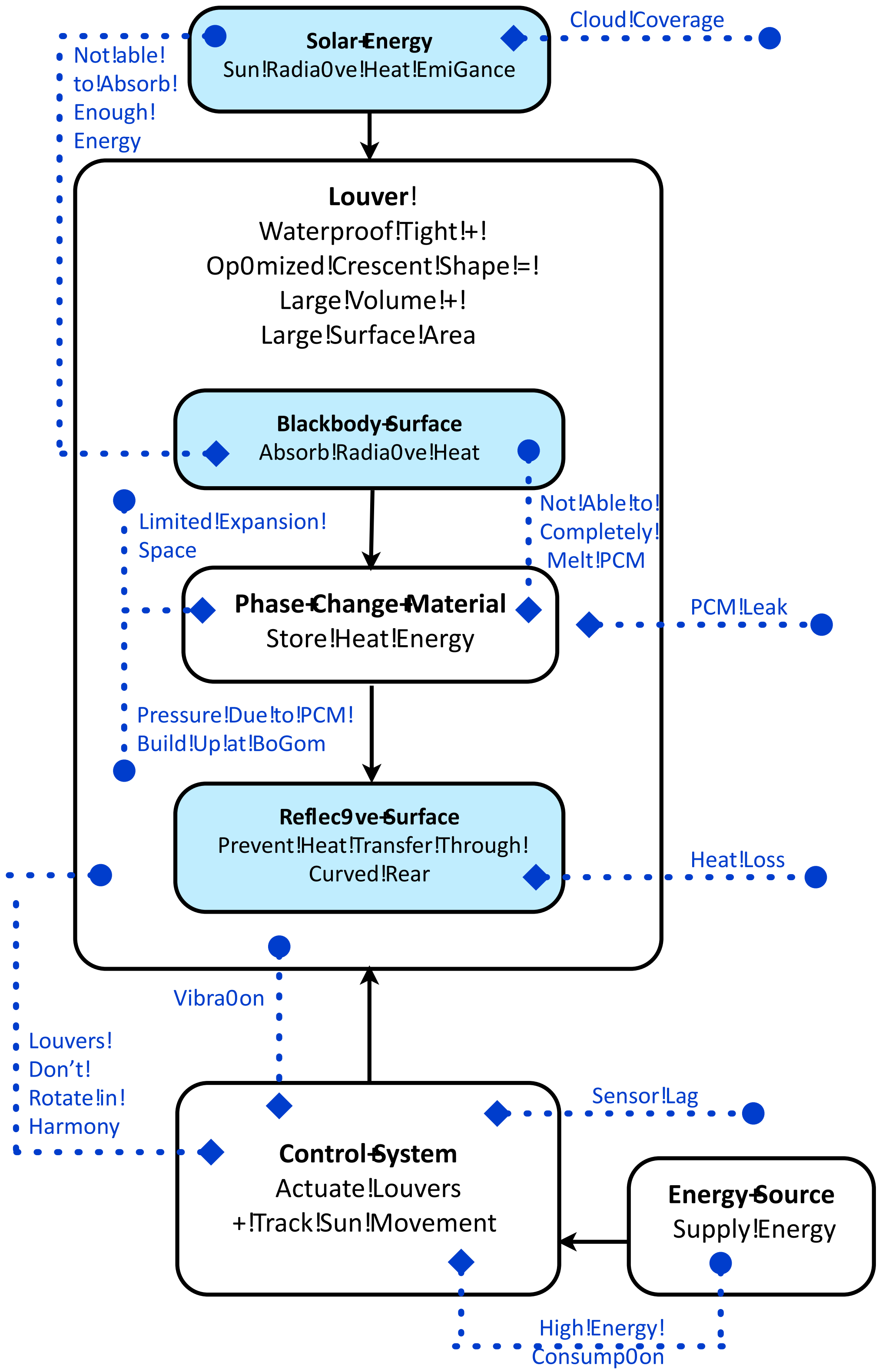


Figure 4: Layout Drawing for Phase Change Material Automated Window Shades identifying major sub-systems, functional groups and potential risks.

Section 2.4: System Layout and Physical Sketch

Originally, our blinds were going to be integrated into the Santa Clara University Solar Decathlon Radiant House; however, due to the high cost of our prototype, and the shortage of aesthetic design, we decided to install our system into Kennedy Commons, a collaboration space on campus which was built to showcase a number of green building innovations. Our team would like to look into mass production and marketing of our product, and are aware of the need to continue the design process with increased focus on aesthetics and cost reduction. Since our project focuses on using solar energy and diminishing the need for electricity or gas heating, potential end users of our product are “green” homeowners interested in saving energy and money. This product can provide benefits to anyone with a need for nighttime heating of their residential space. We hope this could also provide an alternative to wood-burning fireplaces or inefficient electric space heaters. The alternate backbone of our project is to develop a hardy and simple solution to the hot days and cold nights of Northern Africa that does not require advanced infrastructure or education to understand and operate. By simply providing the citizens of the Northern African region with a technology that absorbs the sun's daytime energy and, with the pull of a simple switch, turns to release that energy at night, we hope to provide improved comfort and health to populations in need. This may require a manual actuation system, or cheaper alternate, which we can look further into during the mass production stage. A basic layout of the use of the blind system by the potential end users is shown in Figure 5, outlining how each sub-system makes the product unique and works together to effectively absorb and emit solar energy in a building.

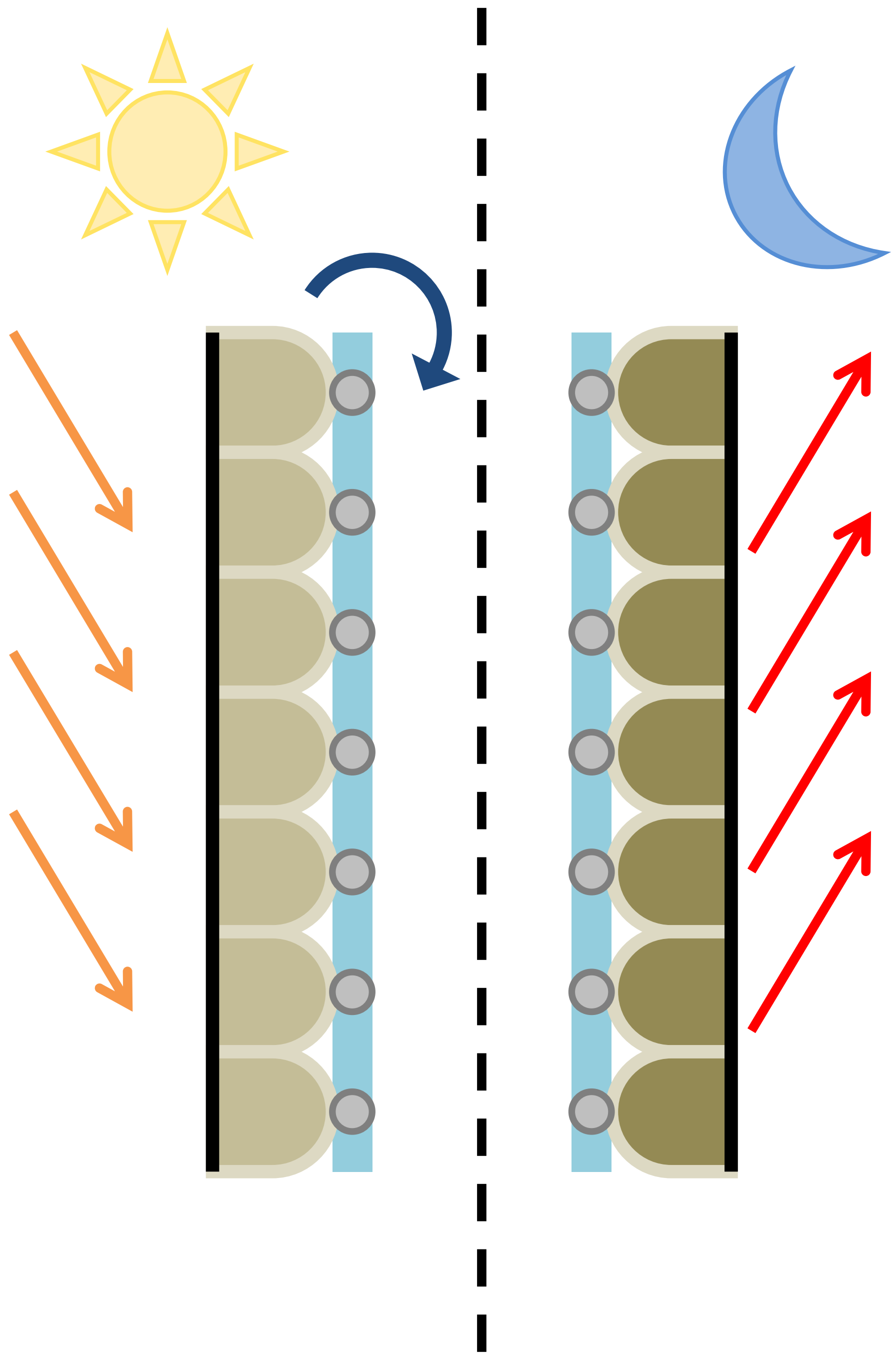


Figure 5: Top view of the rotating louvers with heat absorption during the day and emission at night, in order to replace nighttime space heating.

Section 2.5: Team and Project Management

Meyers-Briggs identified the optimum group of MBTI personality types for product development based on previous studies. We developed our team based on this research and believe that it has been a great benefit to our progress and collaboration on the project.[20] Each member was very willing to step up and take the lead in a variety of situations, but also had the ability to step back and allow others to; with full confidence in the results our team members were capable of producing. We identified Jake as our team lead and generalist to provide assistance on all fronts of the project. He aided in delegation and was the best individual with any calls or face-to-face confrontations that we have to take part in. With his lead involvement in the Solar Decathlon House he provides useful input for the integration and project budget. Quinlan is a Research Assistant for our advisor, Dr. Hohyun Lee, and performed many experiments and analysis on PCMs over the summer. He was delegated as the lead individual in regards to the phase change material calculations and decisions for the final product. Alex is an expert in actuation and control systems, and took the lead in the development of that sub-system of our project. The team was very dependent on his knowledge of code-writing and overall concepts for explanation and integration within the project. Ali joined the group as an organization and details person who was been responsible for setting schedules and ensuring the quality of finish work, two areas that the other three members have struggled with somewhat. In order to complete the report, the organizer gathers availability information and plans meetings to develop the project plan and to set and report on various deadlines.

Challenges and Constraints

The largest challenge we discovered during the process was our ability to make time for the project. All members of the team were more than willing to take on deliverables, but were not always able to meet the desired due dates because of outside commitments. Other classes and obligations put a hold on the fall prototype manufacturing, but once we sat down as a team and realized that we were behind we were able to quickly and succinctly develop a plan to fix the issue. Our team held weekly meetings with our advisor and met at a scheduled time twice per week. Originally, we were completing the many written assignments we had for documentation of the project, but realized that that was a task that could be completed individually and outside of our meetings. We then

[20] "My MBTI Personality Type - MBTI Basics." The Myers & Briggs Foundation. http://www.myersbriggs.org/my-mbti-personality-type/mbti-basics/ (accessed September 25, 2012).

utilized this time to work on the manufacturing, experimentation, and analysis. With this change we were able to meet more of our deadlines outlined in the intended quarterly timelines of Appendix A.5. The theoretical and actual timeline for the year is analyzed in Chapter 12.6.

Design Process

Our team's approach for the design process was very hands on. Though we supported the majority of our design decisions with calculations, the process timeline was centered on manufacturing, purchasing, and testing prototypes of the device to see how the design would operate. The timelines found in Appendix A.5, were the initial outline our team created for the product development process, with some additions throughout the project. With grants funding this timeline, we were able to develop a single-louver prototype, mini-model, and final prototype by the end of the academic year. The ability to tune and adjust physical products allowed us to examine potential successes and failures in the first two prototypes.

The major system components that controlled our design are outlined in the Product Design Specification (PDS) found in Appendix A.1. This is comprised of the system's major components, and includes the phase change material, louver/shade design optimization, control system, and final product design energy evaluation. By equally dispersing tasks, while placing relative experts as the lead of particular subsystems, we created a team culture and process that was able to produce the best possible product for final showcase.

Risks and Mitigations

To guarantee our team worked ethically as a unit, communication is paramount. We held bi-weekly meetings to discuss and ensure that every member was doing their part, while following proper and ethical codes of conduct. If one student was venturing in a questionable direction, the plan was that through simple communication and prodding from the other team-members, the ethical issues would be resolved. As teammates, each member was personally alert to the possibility of another team member turning in plagiarized work, and strict referencing guidelines were set to ensure that all resources and contributors were properly recognized.

We set up a balanced system for workload distribution and decision-making, with each member selecting a job that fits their skill set, and one for which they are comfortable agreeing to due dates. Our close, but professional relationships with one another allowed us to settle differences through conversation and compromise. If the project ventured in a direction negligent of safety, that would cause reasonable harm in production or application, it would have been terminated. Our team would have ceased production if our investors requested an unethical or illegal action to promote or improve the project, such as ignoring or lying about data. The most likely ethical quandary would have been if our team had strong disagreements on ethical limits. If an instance ever arose that a team member did not feel comfortable pushing limits that another might feel is completely ethical, that concern would have been invested further until the entire team was able to come to a consensus. We sought outside input on each decision, and agreed that every team member would need to be 100% comfortable attributing their name and reputation to our final product and the processes used to produce it. After analysis of the requirements within each sub-system of our design project, our team initially determined that the issues outlined in Table 4 as possible risks that needed to be addressed at the start of the process with mitigation strategies for the project development process. Our team successfully avoided any major issues by outlining the potential risks at the beginning of the project.

Table 4: Risk Analysis Chart where Probability [0-1] x Severity [1-10] = Impact → P x S = I.

Risks	Consequences	P	S	I	Mitigation Strategy
Failing Sub-Systems and Overall System	Incomplete project, with need for extended time and restarts.	.6	10	6.0	Continuously brainstorm multiple design options for each component of the system to use in the next trial-and-error iteration. Have the ability to investigate and explain why the system failed, and future possibilities for improvement for the report.
Unfamiliar Concepts	Spend time learning concepts and reiterate calculations.	.3	5	.15	Hold Weekly meetings with advisor to use as a knowledge resource and discuss concepts we are unfamiliar with to reduce time in learning curve.
Conflicting Schedules	Group is unable to meet, make decisions, or ask for help.	.5	5	2.5	Set Bi-Weekly meetings as a team and with advisor to check-in. Signed and verbal agreement to be a self-motivated team member, willing to help beyond assigned role within the group.
Time	Incomplete assigned tasks, and eventual project failure.	.8	8	6.4	Group strategy to hold short Bi-Weekly meetings assign deliverables and disperse to work on objectives individually. We prioritize actions to complete the most important with the time each member has.
Sole Student Decision Making	Rely on calculations and basic knowledge. Increases iterations of trial and error, wasting time and materials.	.5	8	4.0	Our advisor and group encourage the trial and error process in order to learn which materials and processes are ideal for our project. But, after each iteration, we meet as a team to discuss all options from varying points of view, rather than waste too much material and time.

Section 2.6: Timeline

The original timeline that was proposed at the beginning of the quarter was extremely optimistic. The project was expected to take no more than five or six months to complete; a goal that we felt weekly deliverables set every Monday with our advisor would allow us to accomplish. At the start of each quarter, a Gantt chart was drawn up, as shown in Chapter 12, to outline our written, experimental, and hardware-oriented goals for each week. Although we completed all of our deliverables, these quarterly Gantt charts were much too ambitious. They were created with the assumption that Senior Design was the only objective that had to be completed throughout the academic year.

We initially planned on completing the single-louver prototype during the fall quarter to begin testing in the winter, but this was pushed back by a few months due to complications with the testing environment and the completion of the control system. We ran into the same issue with the final system, where we hoped to have enough time to finish assembling the base (as well as all seven louvers) and test the system's efficiency prior to the Senior Design Conference and our Center for Science, Technology, and Society and Lawrence Berkeley National Laboratory presentations. At the time of those presentations, however, we only had a few data points and had to make several hypotheses concerning the results; this was due to the fact that we did not have enough data to make a concrete conclusion at the time of the previously stated conferences.

Over the course of the year, our team learned that the design process (involving development, manufacturing, tuning, and testing) takes a large amount of time, and that very few steps in the design process are completed without a single setback. For example, when manufacturing the base of the louver stand, little attention was paid to the tolerances of the mill and the lathe—this caused some of the rods to be mismatched against the holes that were drilled, which resulted in a final assembly that had to be slightly tweaked to match these slightly altered dimensions. We feel that we had more issues arise than we could have anticipated, but we were able to work as a team to determine a solution to each problem and fix it. Our team delegated a key individual to each sub-system: Jake to manufacturing, Quin to the PCM, Alex to the control system, and Ali to experimentation; however, we quickly found out that a combined team effort produced the best product. One person working on a single sub-section was incredibly inefficient, and this strategy was abolished by the start of January. Once two or three people were working on a single section (this was most prevalent during the manufacturing process), time management skyrocketed while more effort was dedicated to the project.

If this project were to be attempted a second time with the knowledge we gained throughout the design process, we would have front-loaded the work towards the first quarter, so the last month or so of the project would not be so incredibly dedicated to Senior Design. It was determined that even though all the work was completed at a high level of quality, the deadlines during fall quarter were too relaxed. This resulted in some procrastination, which resulted in 30-40 hour Senior Design work weeks during May. To any future Senior Design groups, it would be recommended to avoid this timeline as much as possible.

Table 5: Outline of the original proposed timeline for the design process throughout the year.

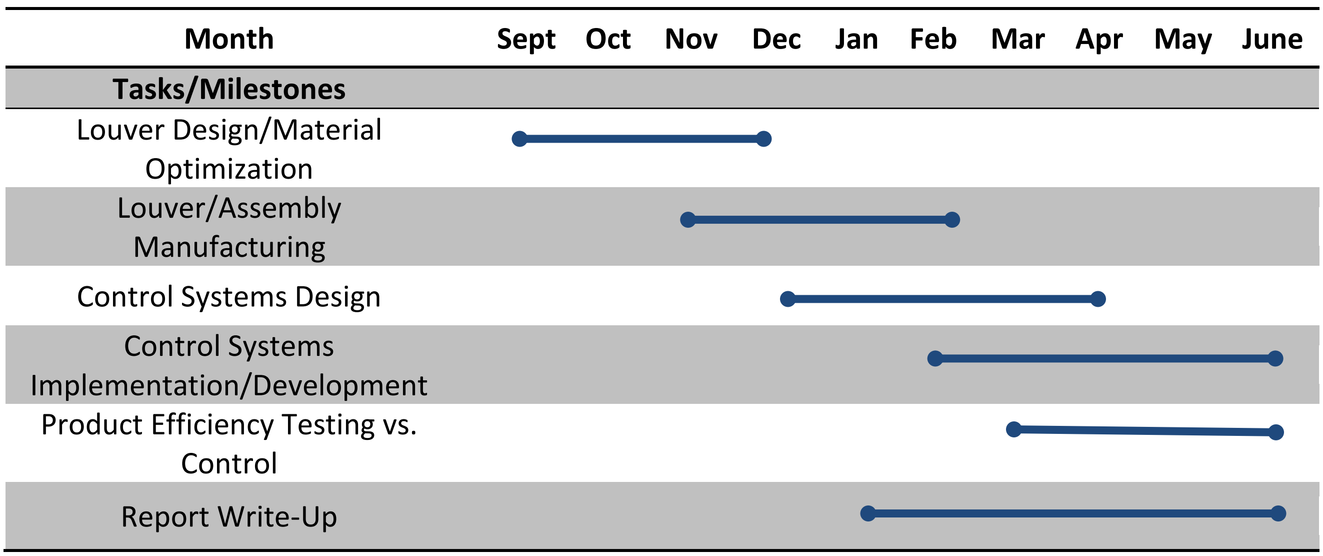
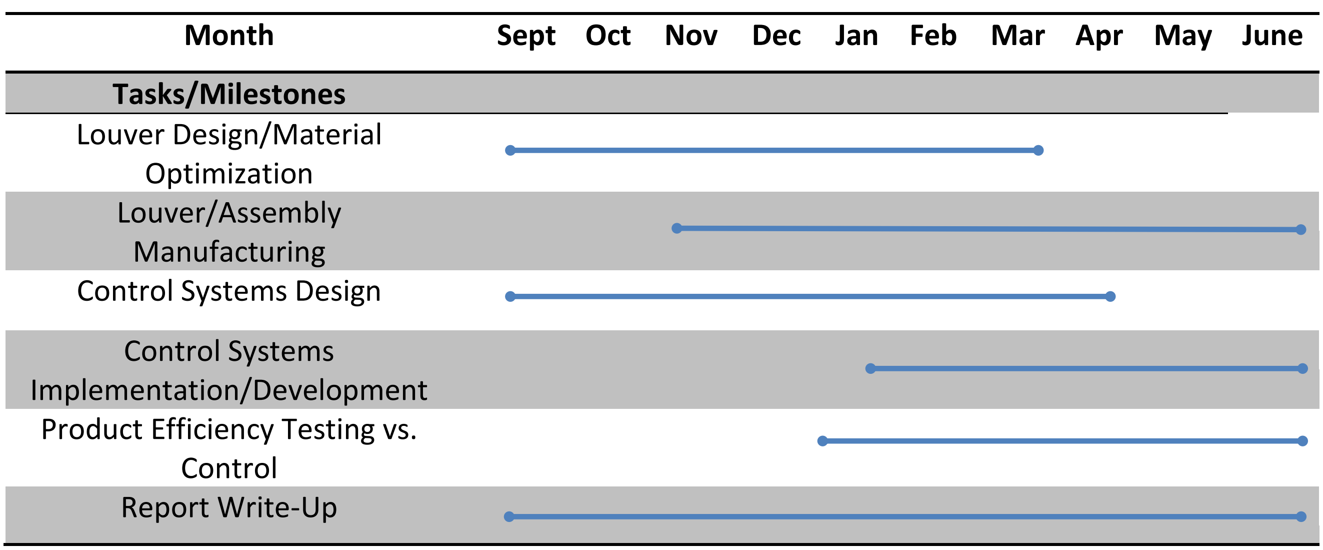


Table 6: Outline of the actual timeline for the design process throughout the year.



Chapter 3: Louver Set

Section 3.1: Description and System Function

There were a number of characteristics that the louvers needed to possess in order to properly serve their function as a vessel used to store PCM, and to optimally absorb, store, and release thermal energy throughout a 24-hour period. In order to best do this, it was determined that the louver would need a front face which could operate with as close to black body absorption as possible. It needed to have an insulative back edge, to prevent the louver from prematurely releasing heat into the interior space during its melting cycle. The construction of the louver needed to be rugged, inexpensive, and fully water-proof even at pressures well beyond those that it was expected to reach. Finally, the volume and surface area of the louver would need to be optimized to provide as high of a surface area to volume ratio as possible, without sacrificing a significant amount of total available energy or volume.

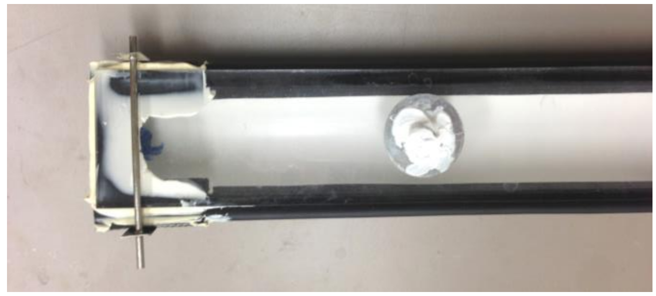


Figure 6: First Iteration of our louver including a water-proof seal and hardware enclosure.

The final louver design was comprised of a black ABS plastic parabola, chemically bonded with two ABS end caps. A sheet of 1/8” acrylic was adhered to the front edges of the parabola to create a water-proof vessel. A thin sheet of aluminum was adhered to the back, inside surface of the louver to act as a radiation shield, and the aluminum face was back painted with black spray-paint to aid absorption.

Section 3.2: Iterations and Design Process

Once the basic concept had been established for the function of the system, one of the first steps was to develop a louver design that would house the selected PCM and could be optimized to absorb, contain, and release thermal energy as needed. Initially, we determined that it would be ideal to use smaller louvers for aesthetic purposes, and thought it would be convenient to be able to open and close the louvers for the purpose of switching in different varieties of PCM during testing. We decided to build the first louver simply: a 2” PVC pipe cut down its center to a length of 3’. PVC seemed to be an ideal material due to its low cost, and low thermal conductivity of 0.13-0.25 W/m-

K[21]. In an attempt to realize the goal of PCM interchangeability, we secured weather-stripping to the edges of the PVC pipe, and used crude clamps made from a steel rod and pipe clamps to secure a strip of 1/8" thick acrylic to the weather-stripping lined edges of the PVC. We quickly determined that the 1/8" thick acrylic was not thick enough when the 3/16" steel rods cracked straight through the acrylic when we attempted to tighten the clamps.

We then purchased much thicker, ¼" acrylic to use for the face of the louvers. While this thicker material was able to endure the stress of the rods and clamps pressing down against the weather stripping, we were ultimately unable to produce a water-proof seal. Weather-stripping was simply not capable of producing a water-tight vessel and in each iteration failed at the four corners and ends of the louvers, despite the addition of water-proof silicone caulking (which, even if had it worked, would effectively have ruined the "easy open, easy close" capability that we were hoping for in the first place).

Figure 7: Second Iteration of our louver utilizing ABS and a greater volume.

At around the same time, a separate thermal analysis determined that louvers with diameters of greater than 2" would be needed to store a sufficient amount of thermal energy. At that point, the decision was made to switch to ABS plastic, which was readily available in larger sizes than PVC pipe, had a similarly low thermal conductivity of 0.17-0.19[22], and had a greater acceptable temperature range of up to 180°F. The one drawback to ABS was that it required a coating to protect it against UV damage. Thankfully, at the same time that we determined that a larger louver cross section would be ideal, we also determined that aluminum foil radiation shielding along the inside back edge of the louver would help to prevent any thermal energy from passing through the backside of the louvers during the day. Given the fact that the only time UV protection would be needed for the ABS would be during daylight

[21] "PVC Hard." *Matbase*. N.p., n.d. Web. 30 May 2013. <www.matbase.com/material-categories/natural-and-synthetic-polymers/commodity-polymers/material-properties-of-hard-polyvinyl-chloride-hard-pvc.html>.

[22] "ABS General Purpose." Matbase. N.p., n.d. Web. 30 May 2013. <http://www.matbase.com/material-categories/natural-and-synthetic-polymers/commodity-polymers/material-properties-of-acrylonitrile-butadiene-styrene-general-purpose-gp-abs.html>.

hours, and that the louvers would be oriented such that the radiation shielding would be protecting the ABS throughout the day, ABS was a perfect candidate for our next round of louvers.

Initially, the increased size of the louvers caused us to worry that the pressure of the PCM at the bottom of the louver might be enough to force at the high pressure, bottom end of the louvers. We also weren't sure if the pressure at the bottom of the louver might be sufficient to increase the melting temperature to a point that we might be unable to melt the PCM during daytime hours. Given these concerns, we attempted to build a "compartmentalized" louver, with water-tight spacers at each foot in the 3' long louver. We abandoned the use of weather stripping, and instead opted to have custom ABS end caps made, which could be chemically bonded to the ends of the ABS louver body. We used a second adhesive to adhere a 1/8" thick acrylic plate directly to the edges of the cut ABS body. While the adhesives worked significantly better than the weather-stripping had, the fact that we only had one chance to lay down a layer of adhesive on each of the ABS partitions before we adhered the acrylic face to the body, meant that we struggled to produce a water-proof seal between each of the interior compartments. Additionally, because the louver would theoretically be made up of several water-proof compartments, several holes were needed on the back of the louver to add or remove wax. This introduced another level of complexity, and a number of additional opportunities for leakage.

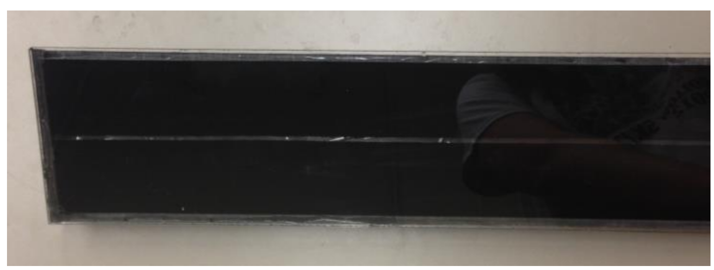


Figure 8: Final Iteration of our quarter-cut louver bound with an expoxy, and incorporated in the final system.

At that point, we conducted a basic analysis of the pressures inside the louver, and determined that the max pressure at the end of a 7' long, 4" wide louver (the max size and length that we thought we might ever use), was calculated to be only 2.33 psi. In contrast, the adhesives that we were using were rated to provide between 900 and 1700 psi of bonding. This, coupled with the determination that the pressure would have a negligible impact on the melting temperature, allowed us to abandon the compartmentalized design, and move on to our third and design.

The third louver was identical to the compartmentalized design, but without the partitions. After building and successfully sealing the first ABS, single-chamber, aluminum shielded louver, and testing various PCMs to select a variety that would melt at the requisite temperature but would still store a significant amount of thermal energy, we realized that the absorptive acrylic face was not an ideal surface or material for capturing solar thermal energy. Wax could be added and removed from this design from a single 1” hole located at the top of the louver, which could easily be plugged when the system was being transported or operated. Consideration was given to creating a lens-like glass hyperbolic face to magnify the amount of solar energy that was received, but custom cut glass was ultimately decided to be too expensive of an option. Instead, we opted to simply back-paint the back side of the acrylic face to produce as close to a black body surface as possible. While graphite had previously been used successfully in lab experiments aimed at determining the thermal characteristics of PCM, it was quickly found to have very little resistance to liquid flow (like that of the melted wax, or, for the purposes of testing, a gentle stream from a hose). The graphite was replaced with a standard oil-based matte black spray paint, which adhered much more solidly to the acrylic surface.

With a working louver design completed, we were able to begin testing, and immediately began seeing strong results. However, as our testing went on, we saw that only about 50% of the volume of the half-cut louvers was melting in a single day, meaning we were using a louver with a lower surface area to volume ratio than was necessary. From there, we built a rig which gave us the ability to make off-center cuts from the ABS pipe. We used the rig to develop our fourth and final louver, the “quarter-cut”. The quarter-cut louver had a diameter that was approximately ½” smaller than the half-cut louver (3.5” inside diameter or 4” outside diameter as opposed to the half-cut louver’s 4” and 4.5”), and held approximately 1/4th less PCM in it than a half-cut louver. The quarter-cut louver proved to perform ideally and melted a full 100% in a single day’s time.

Perhaps the greatest set-back came when the set of louvers, built identically for testing except that one was a half-cut and the other was a quarter-cut, failed catastrophically upon being filled with wax, resulting in major wax spills in the hutches used for testing and in the lab. A number of possible reasons for failure were identified, including: the reduction in thickness of the acrylic face from ¼” to 1/8”, which allowed for greater bending, and the slight over sizing of the acrylic face, which caused the flanges used to connect the louver to the control system to bear on the face itself causing it to bend outward. Ultimately, however, the key source of the failure was tied to a change in the method of spray-painting the acrylic faces. While previous louvers had been masked along their edges to allow for a clean connection between the ABS and acrylic, the failed louvers had been painted right up to the edges, causing a layer of oil-based spray paint to interfere with the glued joint. Further testing of the connection between painted and unpainted ABS to acrylic confirmed the hypothesis, and louver construction was restarted.

Section 3.3: Performance Tests

While many tests were needed to confirm the success of the combined system of louvers, PCM, and controls, the only standalone test conducted on the louvers was a water-proofing test to ensure that each louver could be fully filled with liquid wax, and would not leak over time. In order to accomplish this, upon completion of each louver the louvers were individually filled to max with water, well beyond the ~80% operating fill level, the fill point was plugged, and the louvers were shaken, or sloshed back and forth to ensure that no water escaped. Due to the fact that the louvers were rough cut, and that the adhering was done by hand, many of the louvers failed the first water-proofing test. If a louver did fail a water-proofing test, it was examined to find the point of failure, and glue was iteratively added until the louver passed the test. As is described above, we were ultimately unable to get the first two louver design iterations to acceptably hold water, leading to the development of the third and fourth louver designs.

Chapter 4: Phase Change Material

Section 4.1: Description and System Function

The phase change material (PCM) is the subsystem that is responsible for capturing the sun's thermal energy. The phenomenon that is being utilized is the idea of thermal energy storage (TES), in which the heat from the sun is stored within some sort of material. Two main types of TES exist: sensible heat and latent heat. Sensible heat is stored by heating a material up to a certain temperature: as a material's temperature heats up, the amount of heat it can store per unit mass increases at a linear rate (its units are kJ/kg·K). By contrast, latent heat is stored by changing the state (or phase) of the material (i.e. melting ice, boiling water, etc.). Its units are kJ/kg, and stores *much* more thermal energy than sensible heat storage does. For example, heating one kilogram of water one degree Kelvin stores 4.184 kJ of energy while melting one kilogram of ice stores 334 kJ of energy[23]. Obviously, latent heat storage is preferable if it is possible to implement. In the case of this project, a phase change material was eventually chosen that had the highest possible latent heat of fusion, while still melting at a temperature that could be reached by solar heating.

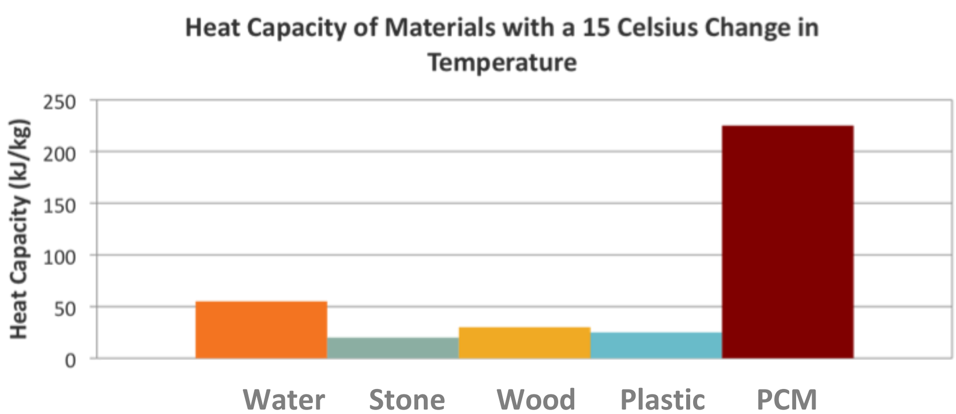


Figure 9: Graph revealing higher heat capacity (thermal energy storage) of Phase Change Material when compared to other common materials.

Paraffin wax was the first discussed option, due to its low melting point and the fact that it is nontoxic, non-corrosive to most materials, and relatively cheap. However, the type of paraffin that was readily available had a melting temperature of 45°C[24], which is unattainable via solitary sunlight heating. Therefore, a different PCM was needed. Rubitherm Technologies, based in Berlin, fabricates

[23] Incropera, Frank P.. *Principles of heat and mass transfer*. 7th ed. Hoboken, N.J.: Wiley, 2013.

[24] Rubitherm Technologies GmbH. Sperenberger Str. 5a, D-12277 Berlin. 49 30 720 004 62.

a wide variety of materials that melt at different temperatures that are cheap enough to purchase in large quantities. Two specific materials were originally purchased (10 kg each), and were tested to determine whether they could function as the PCM in the final design. The first, denoted "*RT 21*," melted at 21°C and had a latent heat of fusion of 134 kJ/kg. It expanded 14% upon phase change (which exerts some additional pressure on the louver system) but melting the material was entirely possible, given that it melts at an ambient temperature of 69.8°F, which is easily attainable during the majority of the year in California. The other purchased material, "*RT 28 HC*," melted at a higher temperature (28°C), yet its latent heat of fusion is much higher, at 245 kJ/kg. If this material can melt within a full day in California, then it is the easy choice to be implemented; almost 1.5 times more energy is stored in *RT 28 HC*, compared to *RT 21*[25].

Section 4.2: Performance Testing

A simple melt/solidification test was performed on each material, to determine the time required to solidify a set mass (~0.5 kg) of melted PCM during the night in mid-January (~8.0°C ambient temperature). There was no need to quantify the experiment numerically, as the *RT 21* did not even solidify past the state of a goo-like substance, whereas the *RT 28 HC* was fully solidified about two hours into the experiment. This confirmed our choice of the *RT 28 HC* as the PCM that was implemented into the final design of the project.

Once the PCM was chosen, some calculations were performed to determine the theoretical melt and solidification times for the PCM under the final dimensions of the louver. An energy analysis was completed, one test each for afternoon and night, for the half-cut and quarter-cut dimensions:

$$q''_{solar} - h(T_{sl} - T_{amb}) - \varepsilon\sigma(T_{sl}^4 - T_{amb}^4) * At = m * h_{sl} \tag{1}$$

where *q''* is the solar heat flux coming from the sun, *h* is the free convective heat transfer coefficient, T_{sl} is the melting temperature of the wax, T_{amb} is the ambient temperature, *ε* is the emissivity of the material, *σ* is the Stephen-Boltzmann constant, *A* is the cross sectional area of the louver's face, *t* is the melt/solidification time of the material, *m* is the mass enclosed in one louver, and h_{sl} is the latent heat of fusion of the material.

[25] Rubitherm Technologies GmbH, Ibid.

Calculations showed that the half-cut louver (4.5" diameter, 36" length) holds 2.80 kilograms of wax, and melts in 4.88 hours—this assumes a free convective coefficient of 5.0 W/m^{2}K, an ambient temperature of 296K, and a solar heat flux of 600 W/m^2. This is an optimal melt time, but the solidification time of 21.2 hours, obtained by setting the solar heat flux to 0.0 and the ambient temperature to 288K, is much too long, as there are not 21.2 sunless hours in a day. By contrast, the quarter-cut design (4.0" diameter, 36" length) holds 2.00 kilograms of wax and theoretically melts in 4.3 hours and solidifies in 18.8 hours. This solidification time is still too slow for practical applications. To combat this problem, silent computer fans were placed underneath so the air is blown parallel to the face of each lover and turned on only at night, so as to expedite the solidification process. These computer fans, which operate at a wind speed of 5.0 m/s, correspond with a forced convective heat transfer coefficient of about 27.0 W/m^{2}K. Calculations explaining how this number was derived are explained below.

The local Reynolds number was first calculated, using the average velocity of the fan:

The Reynolds number was determined to be turbulent, implying an intense fluid flow.

$$\mathrm{Re}_x = \left(\frac{0.5L\cdot \overline{V}}{\nu}\right) = \left(\frac{0.45m\cdot 2.49\, m/s}{5.89\cdot 10^{-6}\, m^2/s}\right) = 193{,}281.5 \Leftarrow \textit{Turbulent} \tag{2}$$

The local Nusselt number, which is related to the average Nusselt number (which can be used to back solve for the convective heat transfer coefficient) was found from the following equation, which is relevant for fluid flow that is parallel to a flat, isothermal plate:

$$Nu_x = 0.0296\,\mathrm{Pr}^{1/3}\left(\frac{V\times x}{\nu}\right)^{4/5} = \frac{h_x\times x}{k} \tag{3}$$

where *Pr* is the Prandtl number of the surrounding air, *v* is the kinematic viscosity of the fluid, and *k* is the thermal conductivity of air. The constants were plugged in, and then the equation was integrated with respect to *x* to determine the average Nusselt number and, from here, the average convective heat transfer coefficient:

$$\overline{h} = \frac{1}{L}\int_0^L h_x\,dx = \frac{1}{L}\int_0^L \frac{0.0296\,\mathrm{Pr}^{1/3}\times k\times V^{4/5}}{\nu^{4/5}} x^{-1/5}\,dx = 26.84\,\frac{W}{m^2K} \tag{4}$$

This value, which is more than quintuple the free-convection flow coefficient that was assumed during the day, was used to calculate approximate solidification times for the half-cut and quarter-cut louvers. Obviously, this change in heat transfer coefficient did not affect the melting time of the wax as the fans were meant to only be used at night. With the newly calculated nighttime heat transfer coefficient, the new theoretical solidification time for the half-cut louver was 6.54 hours, while the theoretical solidification time for the quarter-cut louver was 5.82 hours. Though the half-cut louver had more available energy per louver (2.44 kWh as opposed to 1.19 kWh) than the quarter-cut design, the quarter-cut louver better utilized the phase change that our product was meant to accentuate. A Finite Element Analysis (FEA) was performed to further determine which louver shape was best to emphasize the solidification of the PCM.

Section 4.3: Finite Element Analysis

To perform the Finite Element Analysis (FEA) study in Solid Works, the louver was updated with material properties that matched that of the actual ABS, acrylic, and phase change material. Because stress and strain were not a concern with this FEA, the only properties that were updated were density (kg/m^3), specific heat capacity (kJ/kg*K), and thermal conductivity (W/m*K). A transient analysis was performed, as opposed to a steady state analysis, in order to determine the temperature distribution between each material during the melting and solidification process. What determined the length in time of the transient analysis were the previously discussed heat transfer analyses that were used to calculate the melting and solidification time of the wax (Equation 1).

These values were used as the time allotted for the transient FEA. The Solid Works drawings, shown in Figures 10 and 11, detail the temperature distribution throughout the entire louver after the melting process has taken place. Because the wax does not change temperature as it changes phase, it was meaningless to enclose a drawing of the louver while in the midst of melting; the entire louver would have been one solid color. The pictures below detail the louver and its three subsections at the heat of the day, once the wax has melted completely. As one could guess, the wax that was closest to the acrylic face was the hottest, while the wax at the back (near the ABS) is near its solidification temperature. As the two drawings show, the average temperature of the wax (green) was approximately 3.5°C higher in the quarter-cut louver than in the half-cut louver. This was because the more shallow backing of the quarter-cut allowed the wax to melt and solidify in a faster, more uniform fashion. Table 8 shows the comparison between the Quarter- and Half-Cut louvers, and reveals that the Quarter-cut was the optimum choice.

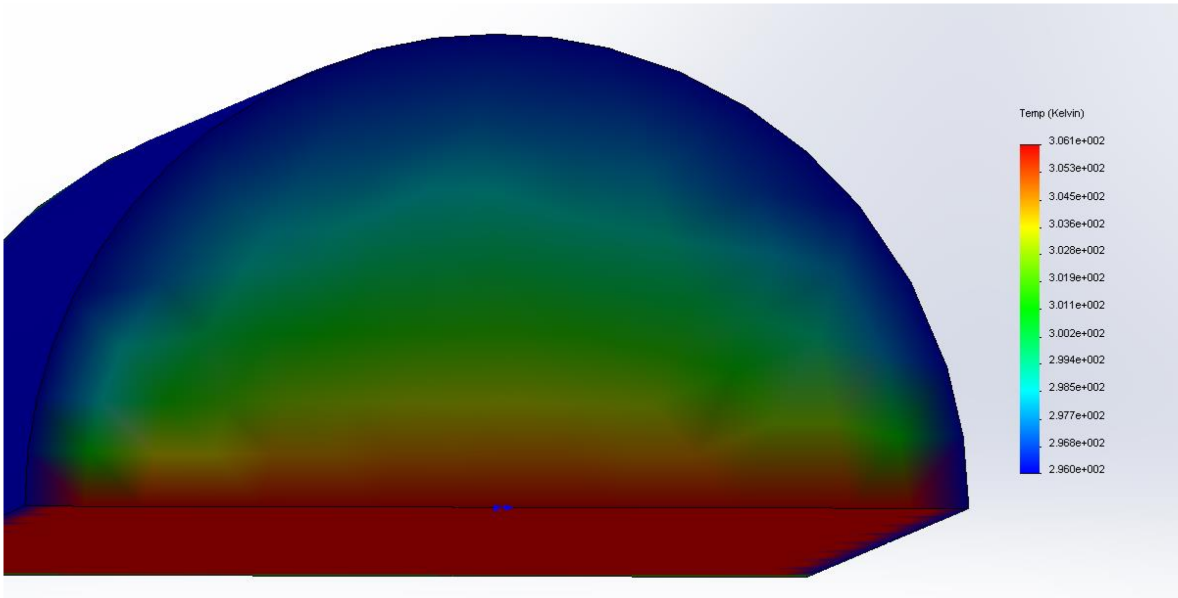


Figure 10: Half-Cut Louver Thermal SolidWorks Simulation analysis.

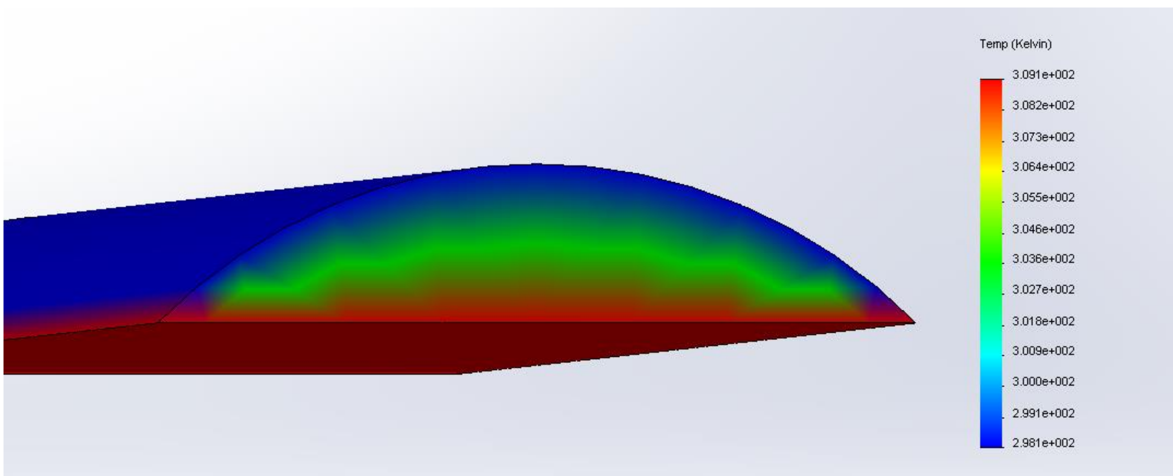


Figure 11: Quarter-Cut Louver Thermal SolidWorks Simulation analysis.

As displayed in the thermal analysis it was more difficult to utilize the benefits of the PCM core as the depth got larger. From the Finite Element Analysis used in SolidWorks, the acrylic faced edge of both louvers experienced higher temperatures than the semi-circular back; this is because acrylic is a highly emissive material. By contrast, the ABS backing of the louver was meant to insulate thermal energy as opposed to absorb it, which is why the back of the louver was the coolest of the sub-sections (ABS, acrylic, PCM). As predicted, the PCM core of the quarter-cut louver exhibited higher temperatures throughout the body as it melted, and the quarter-cut louver was better for melting the PCM core at a faster rate. This confirmed our decision to implement the quarter-cut louvers into the final system, as opposed to the half-cut option.

Table 7: Theoretical comparison between the Quarter and Half Cut louvers which further justified the team's decision to proceed with Quarter-Cut louvers on the final system.

	Quarter-Cut Louver	Half-Cut Louver
Available Energy	1.19 kWh	2.44 kWh
Surface Area per Unit Mass	143.95 in^2/kg	128.59 in^2/kg
Melting Time	4.34 Hours	4.88 Hours
Solidification Time (Without Fan)	18.8 Hours	21.2 Hours
Solidification Time (With Fan)	5.82 Hours	6.54Hours

Chapter 5: Actuation and Control System

Section 5.1: Description and System Function

Currently, phase change material is used in residential and commercial temperature regulation. However, these products do not utilize a control system that can maximize efficiency; this control system could also regulate the direction in which heat is released. Products such as *Thermal Core* by National Gypsum act as a passive thermal storage exterior wall that uses PCM, but the material is not turned to face the sun during the day to maximize heat absorption from the sun. Additionally, when the heat is released as the exterior temperature becomes low enough; it is released both inside and outside the house, wasting some of the energy to the environment.

We made our PCM storage more efficient and predicable, by means of a passive control system. First, we wanted to force the face of the louver to remain perpendicular to the sun's rays to maximize energy absorption. This works to use as much of the available thermal energy to melt the PCM during the day. We also wanted to have control over the direction in which the heat is released when the wax starts to solidify. We wanted to do all these things while using the least amount of energy to power the control system as possible. To do this, it was deemed most energy efficient to allow the face of the louvers to follow the sun's trajectory during the day; at night, the faces of the louvers are turned inwards to force the stored thermal energy into the dwelling.

Section 5.2 Control System Iterations and Design Process

Two important decisions had to be made before work was started on the implementation of the control system. The first of which was to decide on the use of active or passive solar tracking. Active solar tracking involves the use of a sensor array to sense the location of the sun and, using a feedback control system, track and follow its position. Passive solar tracking utilizes the predetermined azimuthal and elevation angles of the sun (based on time of day and location on the globe) to instruct the system on the direction to face. Initially it was decided to start with passive solar tracking, because it is cheaper and simpler to accomplish then active solar tracking. Since a low cost benchmark was important to us, this seemed to be a reasonable starting point.

The next important decision was whether to turn the louvers horizontally or vertically. The decision was to be made once it was determined whether more energy would be captured by following the sun's elevation change or azimuthal angle change throughout the day. A few factors went into this decision, and ultimately we decided to use vertical blinds, because the sun typically sweeps out a larger angle in the azimuthal direction then in the elevation direction at our test location (Santa Clara, CA). Therefore, the face of the louvers would be perpendicular to the sun's rays for a larger portion of the day with the vertical blinds. Also, with the design requirement for a window that was taller than it was wide, vertical blinds would use less louvers than its horizontal counterpart and would therefore be simpler to build. One reason we were concerned about vertical blinds was a worry that the pressure increase at the bottom of the louver would make it more difficult for the wax to fully melt. However, these concerns were later proved to be unfounded during testing when we found that the wax was able to melt completely.

First Control System Iteration

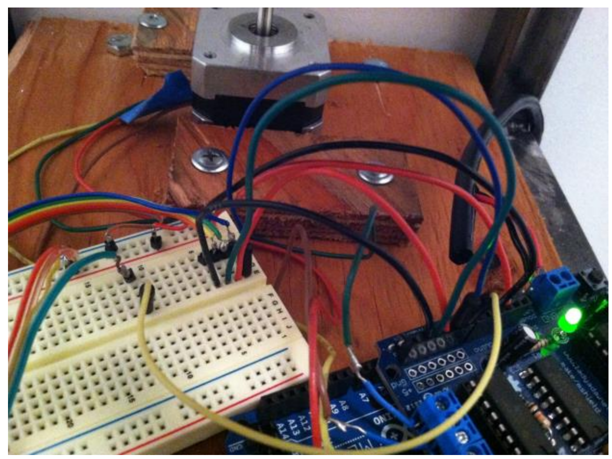


Figure 12: First Iteration of control system setup consisting of an Arduino, stepper motor, and computer running LabVIEW VI.

A spreadsheet was created with a column of times throughout the day starting at midnight, and a column of the equivalent azimuthal angles of the sun for that location and date. The file used for our preliminary tests can be found in Appendix A.6. Originally, the times started at midnight and increased every 15 minutes until 11:45 PM. The angle input when the sun was below the horizon was designed so the face of the louver pointed into the house during this time. Lab VIEW was used by taking the current time of day converting it to seconds since midnight, and outputting the corresponding azimuthal angle of the sun for that time. The Arduino toolbox was installed for Lab VIEW, and an Arduino Mega with a motor shield was connected to the computer running Lab VIEW. A 12V, 0.33 Amp stepper motor with 1.8 degrees per step and 2.3 kg*cm torque was then connected to the motor shield, Adafruit Motor/Stepper/Servo Shield for Arduino kit - v1.2, and a 300 degree potentiometer was connected to the Arduino as well, with the high pin connected to 5 volts and the low pin to the Arduino ground. In the Lab VIEW code, the potentiometer was used to read the angle of the louver. The stepper was then moved step by step until the error between the actual angle read from the potentiometer and the desired angle read from the spreadsheet was within a 2.0°. This degree difference was chosen because this offset from perpendicular only reduces heat transfer by 0.6%. The Lab VIEW code and pictures of the set up can be seen in Appendix A.6. This system worked constantly, though it used a considerable amount of power with the stepper constantly drawing current to hold its position.

Second Control System Iteration

A few changes were made in the second iteration of the control system. The same passive solar tracking system with a spreadsheet input was used: however the stepper motor was replaced with a servo motor and the computer running Lab VIEW for the control VI was replaced with Arduino code and a DS1307 clock module, and a LSM303 Breakout Board - Tilt Compensated Compass was also added. The stepper was replaced with a servo motor because a servo has internal angular feedback, and therefore the potentiometer to find the angle was no longer necessary. A servo also uses less power because it draws much less current when it is stalled at the desired position. Steppers typically have more torque at low speed applications. Yet, because of the other benefits of the servo, we decided that if we could find a servo with enough torque for a cheap enough price, it would be a better option than the stepper. The code previously on the computer in Lab VIEW was rewritten solely on the Arduino to reduce the size and power consumption of the control system hardware. This code is also shown in Appendix A.6. However, a clock module was then needed to keep track of the time so the system could compare the actual time with a time on the spreadsheet. A digital compass module was also added to the system to allow the user to calibrate the system in a more automatic fashion. Previously the system had to be calibrated by hand by comparing the reading for the direction the louver was facing with an actual compass. With the digital compass, the system could be set down in any orientation and it would automatically recognize which way it was facing and point the louver accordingly.

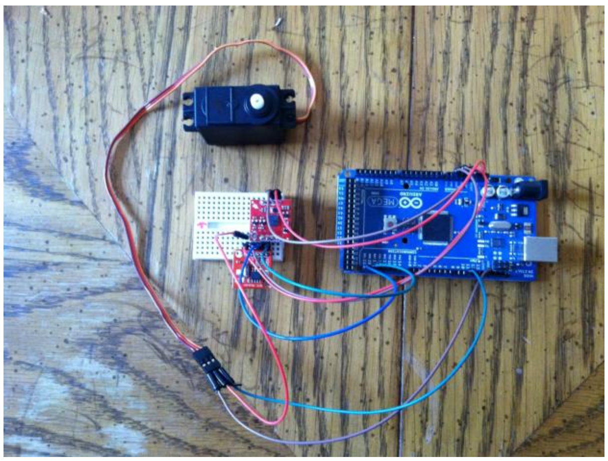


Figure 13: Second Iteration of control system setup consisting of Arduino Mega, compass and clock chips, and servo motor.

Section 5.3 Actuation System Iterations and Design Process

The purpose of the actuation system was to transmit torque from the motor to each louver and to have the angle of each louver match the angle given by the motor. Once it was decided that the louvers would be faced vertically, a few options were considered for transmitting the motion from the motor to the louvers. These options included a drive screw that turns worm gears, a belt and gear system, a rack and pinion system, and a crank system.

Originally the crank system was designed to actuate the movement of the louvers. The motor would turn a crank which would in turn sweep around a long bar in a plane (with cranks connected to it) which would turn each louver. The system consisted of parts made of Delrin (to reduce friction) and aluminum (to keep it light), and was relatively cheap. However, it had the potential to be difficult to manufacture and did not allow for close spacing of the louvers depending on how long the cranks arms needed to be. Therefore another iteration was designed.

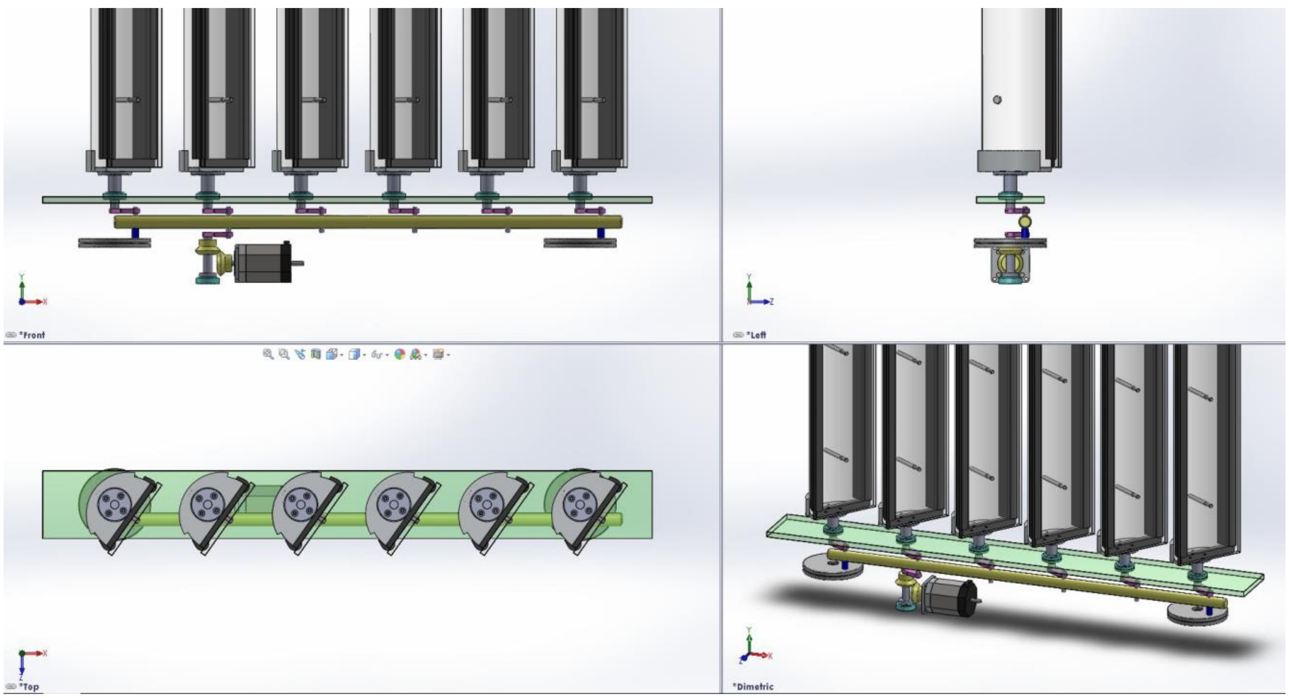


Figure 14: Original design for a crank actuation system with side, top, and isometric views of arm-levers utilized to turn each individual louver.

The second iteration was a rack and pinion system. It consisted of a worm gear that was turned by the motor, which then slid a rack back and forth. This rack was connected back to back with another rack with an aluminum plate between that slid on bearings. This other rack then actuated spur gears that turned the louvers. This system was preferable over the crank system because it was simpler to assemble and because it was easier to change the spacing of the louvers depending on the size they needed to be.

This rack and pinion system was built inside a frame to which all the other support members were fixed. Two rows of aluminum plates were fixed horizontally to the frame: one above the other with the rack and pinion system between them. Holes were drilled in the top set of aluminum plates, so the rods with the spur gears could protrude through and connect to the louvers. Flanges were then connected to the end of the rods and the louvers were glued to the flanges. To allow the louvers to more easily turn, taper bearings were pressed into the top of the plates to allow the flanges to rest on them and allow the louvers to turn with lower magnitudes of friction. The rods that went through the upper plates and the worm gears then continued down into the lower plates which had bearings pressed into them to allow the rods to turn with less friction. Calculations were performed to confirm that the frames and upper plates were strong enough to support the louvers. It was found that with a 3.5’ louver, a frame made of square hollow steel tubes with sides half an inch long and a wall thickness of 0.06” could be given a factor of safety of over 5, which was deemed acceptable. A similar calculation was performed with the top plates at a thickness of 0.25”, and it was found that a similar factor of safety existed, and was also deemed acceptable. The calculations are shown in Appendix A.17.

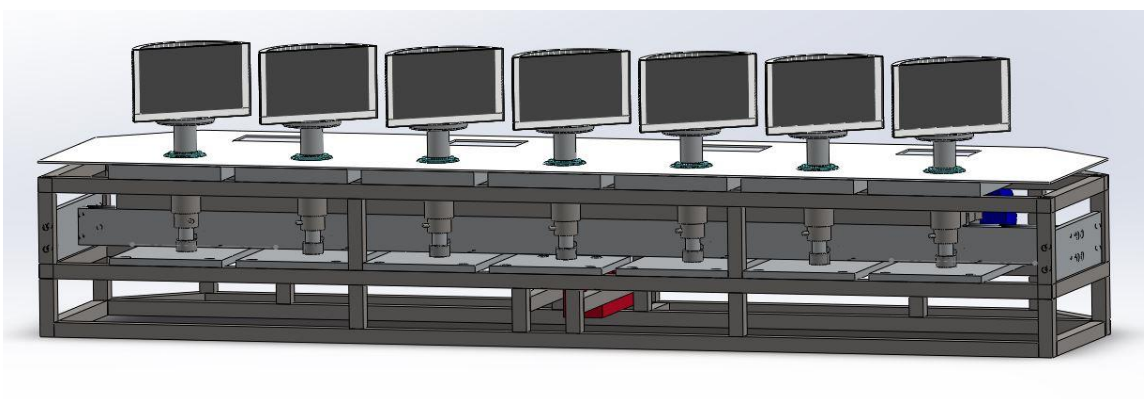


Figure 15: Current design for a rack and pinion system which resulted in ease of movement and allows for a variety of louver sizes to be used without interference.

Section 5.4: Performance Tests

Basic tests were performed on both the control system and the actuation system. To perform preliminary tests on the control system, a sensor array consisting of two photo resistors, each 45 degrees off in the horizontal plane from parallel with the louver face were attached to the face of the louver. The system was run during the middle of the day with the louver turning to face directly at the sun every 15 minutes. The sensor is shown in Figure 16 and its associated wiring diagram in Figure 17. Figure 18 shows the resulting difference in output voltage of the voltage dividers between the two sensors. The horizontal axis is the time (in seconds) since the test was started and the vertical axis is the change in voltage between the two sensors.

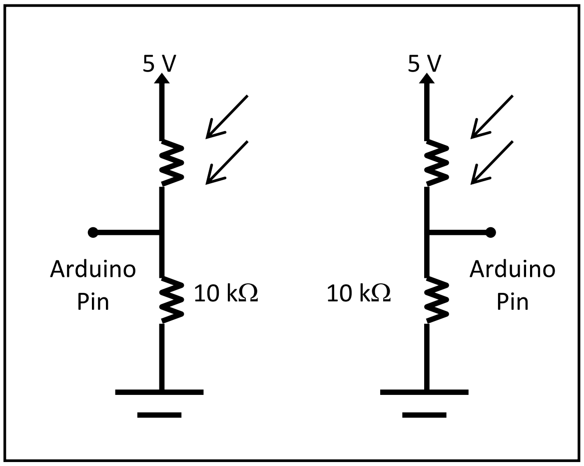


Figure 16: Wiring Diagram for sensor used for control system testing.

The Experimental protocol, shown in Table 8, outlines this specific experiment. The photo resistors used were Token PGM Series, and in order to establish the photo resistor's characteristics it was specified on the Technical Data Sheet that light resistance is measured at 10 lux with standard light A (2854K-color temperature) and a 2 hour pre-illumination at 400-600 lux prior to testing.[26] Dark resistance is measured at 10th seconds after closing 10 lux. The Gamma characteristic is given by

$$g = \frac{\log(R_{10}/R_{100})}{\log(100/10)} = \log(R_{10}/R_{100}) \qquad (5)^{27}$$

so it is dependent on the resistance under 10 lux and 100 lux, and the tolerance of γ is $\pm$ .01.

We saw that the difference in sensor voltage was consistently around 10, which shows that the louver had a small consistent lag. This was likely because the times inputted to the louver were not adjusted for daylight savings time. This sensor test was also not very accurate, and cannot be quantifiably relied upon. Visual tests were also performed to observe that the louver was pointing approximately at the sun. It was also found that with the control system

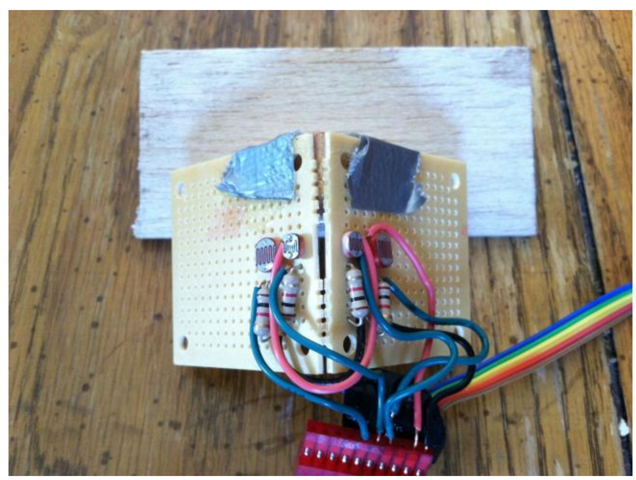


Figure 17: Sensor utilizing photo resistors for control system lag testing.

[26] "Token PGM CDS Photo resistors." *CDS Light-Dependent Photo resistors*. N.p., n.d. Web. 15 Apr. 2013. <www.token.com.tw/pdf/resistor/cds-resistor-pgm.pdf>.

[27] Ibid, "Token PGM CDS Photo resistors."

running on the one-louver prototype, the quarter-cut louver was melting with consistency on sunny and partly cloudy days. This showed that the control system was performing its function of melting the PCM during the day while using minimal energy.

When the actuation system was assembled, basic strength tests were done on the base, and it performed to the required specifications of supporting seven 3.5 foot louvers. The rack and pinion system was also tested, and it ran smoothly, turned the louvers simultaneously and consistently. However, because of tolerance issues in creating a system where all the gears were the same distance from the rack, more friction existed than was desirable.

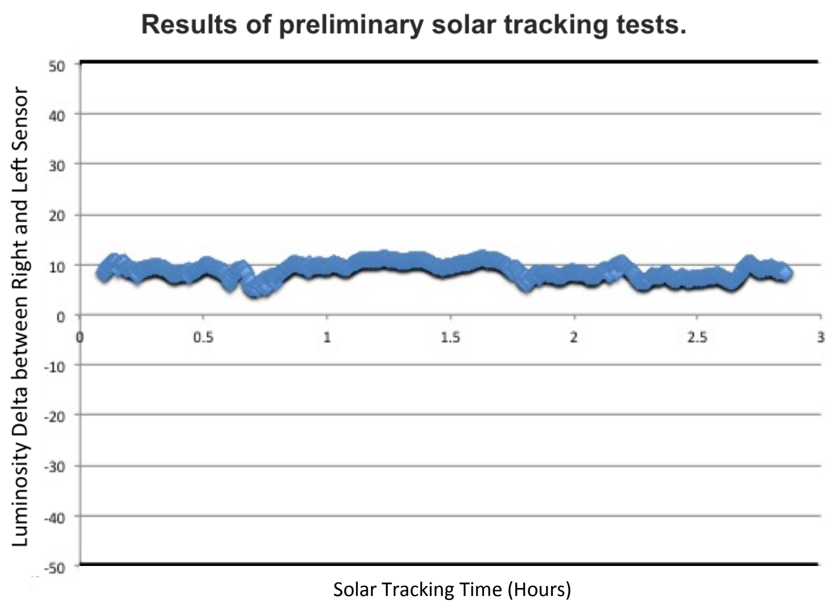


Figure 18: Graph resulting from the delta between the two sensors on the louver face. Plus and minus 50 approximately represents off from perpendicular by about 90 degrees.

Chapter 6: System Integration, Tests, and Results

Section 6.1 Manufacturing and Assembly

The manufacturing and assembly process taught us a great deal about the realities of what can and can't be made, and how easily it is to do so. From the very first process, the construction of the louvers, we discovered that our conceptions of how easy it would be to create a water-proof vessel were far different from what it would actually take. We began trying to use weather-stripping, pipe clamps, and eventually silicone caulking to try and produce a water-tight seal between our louver body and the acrylic face, but soon found out that weather-stripping isn't an ideal material for that particular job, and were ultimately unable to provide the seal. We also had to rethink our design process, when a pair of louvers failed severely and suddenly, causing several pints of wax to spill into our test hutches and lab. By examining the failed louvers, we were able to determine that, despite multiple contributing factors, an attempt to cut corners by not masking the edge of the acrylic face where it was adhered to the louver body was likely the main cause of the spill.

Figure 19: Manufacturing-lead Jake Gallau preparing for installation of hardware on a previous louver design.

The machining and manufacturing of our metal base and actuation system also was quite a learning experience. We recognized that we were confined to the manufacturing tools and practices available to college students, but, due to the uncertainty over the size and weight of the louvers that were to be used in the final assembly, we chose to over-design the base structure by what would ultimately be several orders of magnitude. While the first, crude, single-louver prototype only took a few hours to assemble, the second prototype, or the mini-model, took upwards of 20 hours to machine and assemble. The construction of the mini-model, which was comprised of steel tubing and bolted-on aluminum components, was not well planned, leading to significant delays in its construction. One specific issue came to light when it was time to drill the holes in the steel base that the aluminum parts would be bolted through. Because the steel base was assembled with no thought to the final assembly process, we had to bolt the steel base onto a mill, and purchase a 12" long, extended reach drill bit to drill holes through interior components in the base.

This process took several hours, when it could have taken only a few short minutes if we had recognized it before the steel base was assembled.

Another detail that we didn't fully consider was the importance of tolerance stacking in the design. As was previously stated, our base was significantly over-designed and required quite small tolerances to operate successfully. Because the base was built for modularity as a series of high tolerance aluminum parts, which was then fixed to a very low tolerance welded steel base, there were significant issues when it came time to attach all of the aluminum parts. Several hours were spent filing down the welds to allow the aluminum parts to fit in the required spots, because very little space was given between the aluminum parts and some of the steel support tubing. It is likely that the clashing steel supports weren't even needed to support the upper deck of the steel base, meaning the time spent filing (in addition to the time spent welding in the supports) was wasted.

Section 6.2: Testing Environment and Calibration

Figure 20: Hutch A and Hutch B used for analysis of our system. First configuration resulted in one hutch shading the other.

Before we could even begin the manufacturing and assembly of our single-louver prototype and final system, we had to prepare a test bed and conditions to allow us to test and evaluate the performance of our system. In order to do this we decided to utilize two structures, which we quickly began referring to as "the hutches" that had been built to have identical thermal characteristics, and were installed with double-pane windows and standard insulation in their 2' by 4' framed walls. The hutches were configured to measure indoor and outdoor temperature, luminosity and energy consumption. The initial set up, shown in Figure 20, was oriented such that the windows faced to the southeast and the hutches were side-by-side. We wanted to have the windows face in a southern direction since the sun rises from the east and sets in the west, with the maximum exposure during the afternoon as the sun crosses the southern sky. We quickly discovered that this set up caused one hutch to the other, thereby decreasing the temperature and causing dissimilar environments. After several small shifts to the location and orientation of the hutches, we finally came positioned them in the staggered, southwest-facing, un-shaded configuration shown in Figure 21. Unfortunately however, we still saw some variation in the comparative indoor temperatures of the hutches. To this day, we aren't entirely sure why we were not able to show equivalency between the hutches, but suspect some original small differences in their construction, coupled with differences in how they have weathered over the 10 years since they have been built may have been the main factor. Since we were unable to establish that the hutches would maintain the same luminosity, energy consumption, and temperatures each day, we opted to establish a Hutch A and Hutch B. Both Hutch A and Hutch B were equipped with indoor and outdoor thermometers, luminosity sensors, and Watts Up meters to measure energy consumption. Each hutch also included an indoor heater that was set to a temperature of 24 °C (75 °F). The idea behind this setup was that when the temperature decreased, the heaters would kick on and consume energy. If our PCM blinds worked as intended, the heat energy would be emitted to the room, the heaters would not turn on, and the hutch would consume less energy to remain warm than the hutch without the PCM blinds. The experimental setup as described and as it was utilized for both the single louver prototype and final assembly is shown in Figure 23 below.

Figure 21: Staggered hutch configuration did not produce equivalent testing environment but was used for the revised experimental setup.

As was previously stated, the construction of the experimental environment proved to be one of the most difficult stages of our design process. During the continuous movement of the hutches, our team chose to build a single-louver prototype, shown in Figure 22, in order to evaluate the performance of various louver designs, including the quarter and half-cut louvers, which were the two designs considered for use in the final system. Since we were only able to test the single-louver prototype during the period in which the hutch locations were frequently being altered, we were unable

Figure 22: Single-louver prototype aided in decision to utilize the Quarter-cut louver in the final system.

to produce consistent results showing a significant decrease in energy consumption. What we quickly discovered was that the quarter-cut louver consistently melted and solidified completely throughout the day and night, whereas only half of the PCM core of half-cut louver melted during the day – though it did also completely solidify at night. This proved that solidification was successful without a fan, thereby eliminating the need for a fan which we had calculated would be necessary to achieve expedient phase change. These results, which showed that through quarter-cut louver consistently went through the entire phase change process, thereby utilizing the full thermal energy storage capacity of the PCM confirmed our decision to use the quarter-cut louver. It was our intention at that point to perform our final experiment with the experimental set-up as described above and in Figure 23 below. We expected to see a decrease in energy consumption and luminosity, as well as temperature consistency at or above 75° F.

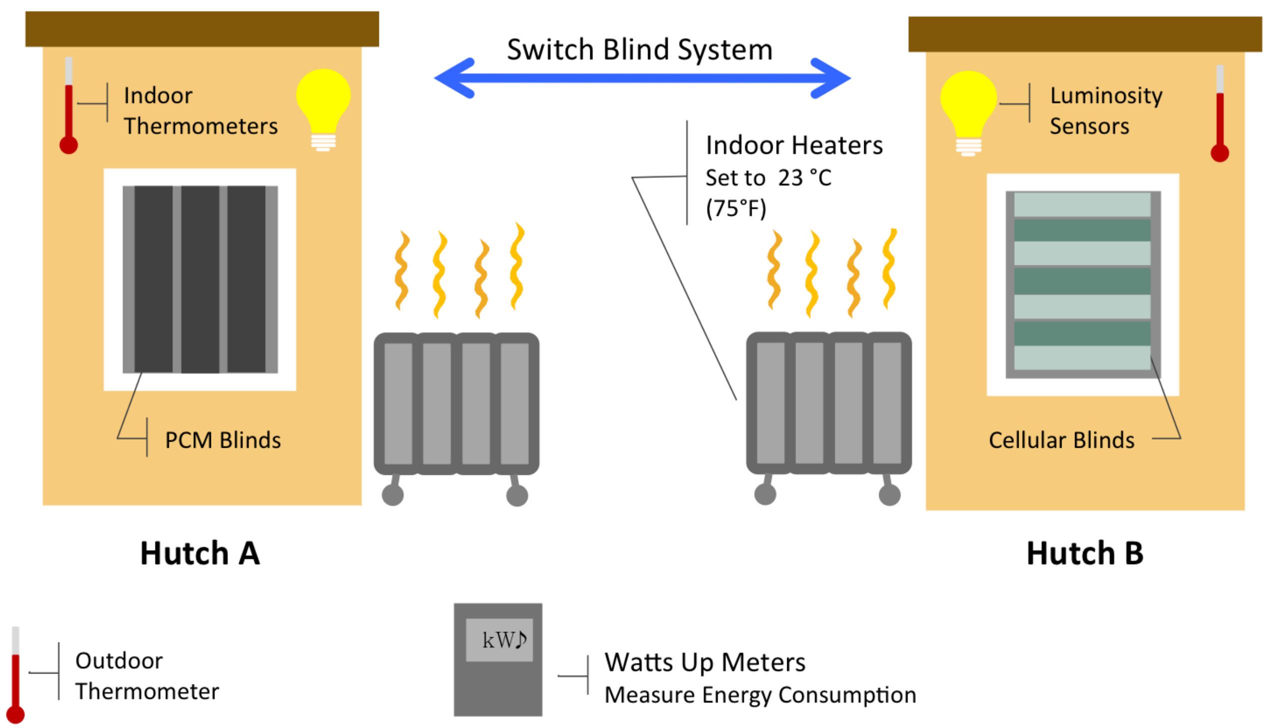


Figure 23: Experiment setup used to analyze and evaluate the Blind system consists of two structure, one experiment and control hutch, including luminosity sensors, thermometers, and Watts Up meters to measure energy consumption.

Section 6.3: Final System Experimental protocol and Results

Prior to experimentation, we utilized the Product Design Specification (PDS) found in Appendix A.1 to develop a list of evaluation criterion for our final system. This development led to the experimental protocol shown in Table 8 which identifies tests that we thought would be necessary for analysis of the control system and overall final blind set. As was stated previously as can be found in Section 5.4, the hutches included luminosity sensors, indoor and outdoor thermometers, and Watts Up Meters to measure energy consumption. The Watts Up technical specifications state that the accuracy of the unit is +/- 3%, +/- 2 counts[28] of the displayed value for loads above 10 watts and is +/- 5%, +/- 3 counts of the displayed value for loads below 10 watts. Counts are defined as the least significant digit, so a tenth of a watt would be the least significant digit shown for a 100 watt load. Therefore, the meter would display 100 +/- 3.3 if a 100 watt load was measured because 3% of 100 watt is 3, plus 3 counts which is equivalent to 0.3 watts, for a total 3.3 watt tolerance.[29] This means the meter will read between 96.7 and 103.3 for the actual 100 watt load of energy consumed. The initial use of the Watts Up meter was for calibration of our testing environment and equipment, though we soon found out that the meters could be useful for determining the equivalency of the hutches; if each meter was outputting a different value, we would know that the hutches had to be reoriented.

The luminosity sensor was custom built to specifications as shown in the circuit diagram, Figure 24. The full error analysis for accuracy included specific error values from the photo diode, resistors, op amp, and the ADC as shown, while additional error could be attributed to the apparatus, environment, and users. The uncertainty for the time constant was based on the calculations and results for the overall experimental uncertainty as well. The following sensitivities are documented from the component manufacturers' schematics:

BPW21R Silicon Photodiode: ± 9 nA/lx[30]

LM324 (ACTIVE) Quadruple Operational Amplifier: ± 2 nA[31]

LM308 Operational Amplifiers: ± 0.2 nA[32]

(3) Resistors: ±1%

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[28] "Watts Up? Support." *Watts Up? Pro Technical Specification*. N.p., n.d. Web. 15 Apr. 2013. <https://www.wattsupmeters.com/secure/support.php?pn=12>.

[29] Ibid, "Watts Up? Support."

[30] "Silicon Photodiode BPW21R Specification." *Vishay Semiconductors*. N.p., n.d. Web. 5 Mar. 2013. <www.vishay.com/docs/81519/bpw21r.pdf>.

[31] "LM324 (ACTIVE) Quadruple Operational Amplifier Specification." *Texas Instruments*. N.p., n.d. Web. 15 Mar. 2013. <http://www.ti.com/product/lm324>.

[32] "LM108/LM208/LM308 Operational Amplifiers Specification." *National Semiconductor*. N.p., n.d. Web. 15 Mar. 2013. <http://web.mit.edu/6.301/www/LM108.pdf>.

These error values have varying units, so using the equation for uncertainty,

$$u_x = \sqrt{u_1^2 + u_2^2 + ... + u_k^2} \qquad (6)^{33}$$

helped to establish a consistent instrument uncertainty for each. The first-order uncertainty is an estimate of the error produced from using each instrument, and may also include human error.

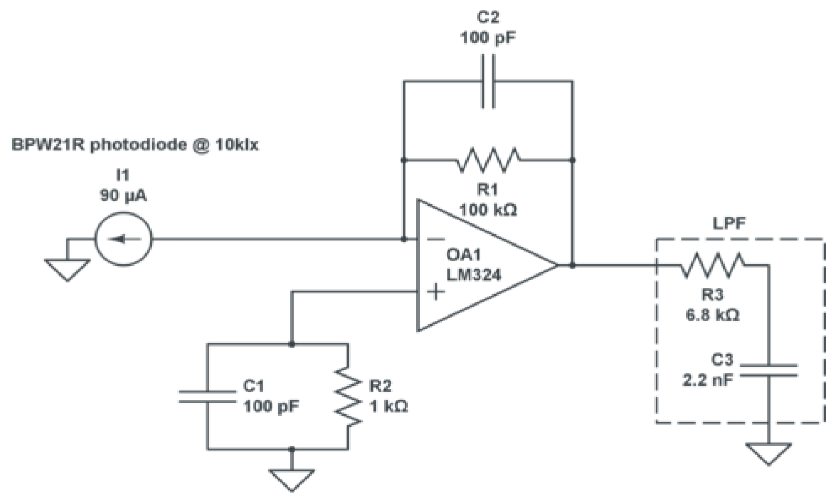

Figure 24: Diagram for custom built circuit for the luminosity sensor, including a photo diode, resistors, op amp, and ADC, all with their own sensitivity.[34]

[33] Figliola, R. S., and Donald E. Beasley. *Theory and Design for Mechanical Measurements*. 5th ed. Hoboken, NJ: J. Wiley, 2011, 165.

[34] Barker, Laughlin. "Circuit Lab."*Transimpedance Amp*. N.p., n.d. Web. 15 Mar. 2013. <https://www.circuitlab.com/circuit/g7t4a9/transimpedance-amp/>.

Table 8: Experimental protocol for control system and combined final assembly.

Evaluation	Location and Time*	Equipment**	Accuracy	Trials ***	Expected Outcome	Assumptions	Man-Hours
Accuracy of Control System Response		Cadmium Sulphide (CdS) Photo Resistor	$\gamma \pm .01$[35]	3	10%	Photo Resistor's Response: Rise and Decay Time are 20 and 30 mSec.	6
Melting Time		Visual/Video Camera	Human Error ± 30 Minutes	4	(Hours) Quarter: 4 Half-Cut: 4.4	Accuracy approximated based on variability between experimenter on establishment of fully melted or solidified.	10
Solidification Time		Visual/Video Camera		4	(Hours) Quarter-Cut: 8 Half-Cut: 10		
Overall Blind Coverage/ Light Passage	Hutches at Solar Decathlon Site/ (May 15 – June 15)	Luminosity Sensor: Si Photo-diode, Res-istors, Op Amp, and ADC	± 9.22 nA[36]	7	10%	Equivalent test environment and window size. Calibration tests in process.	14
Thermal Energy Capacity		Watts Up? Pro	± 5% ± 3 Counts (Watts)[37]	7	6000 kJ	Equivalent test environment and heaters set to 75 °F. Calibration to ensure similar heater energy consumption and temperature.	
Energy Savings		Watts Up? Pro		7	1.6668 kWh		
Consistent Temperature Increase		Type K Thermo-couples	± 1.5 °C[38]	7	3-5° Increase		
Calibration of Testing Environment		All of the Above	All of the Above	60	Equivalent Testing Environment	Dependent on varying weather conditions.	40

*Assuming completion of final system and calibration of hutch location for optimum testing environment by May 5, 2013.
**Excludes uncertainty of Compact DAQ, Input Modules, and Lab View software programs. (To be included with experimental data.)
***One trial is equivalent to a 24-Hour Period (12 PM – 12 PM), and number of trials may be doubled depending on variability in weather conditions during that week.

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[35] Ibid, "CDS Light Dependent Photoresistors."

[36] Ibid, Barker, Laughlin.

[37] Ibid, "Watts Up?."

[38] "Thermocouple Type K | Type K Thermocouple | Chromel/Alumel Thermocouple." *Thermocouple, RTD Sensors, Bearing Sensors, Thermowells, Flanges, Thermocouple Types, Temperature Sensors*. N.p., n.d. Web. 15 Apr. 2013. <http://www.thermometricscorp.com/thertypk.html>.

Upon completion of the tests listed in the experimental protocol, an evaluation was performed and results summarized in Table 9. The initial evaluation of the control system as it was outlined in the previous chapter met the expected outcome. The original melting and solidification tests as outlined in Chapter 4 were performed and showed that RT 28 HC fully melted and solidified in approximately three and two hours respectively in the ambient outdoor California temperature during an average January day. Our results, tabulated in Appendix A.11, showed that on an average day during March in California the quarter-cut louver took 4.6 hours to melt and approximately 8.0 hours to solidify indoors, whereas the half-cut louver took 5.9 hours to melt and consistently did not solidify completely at night. All of these times were greater than our expected outcomes, but had a maximum percent different of approximately 20%, not including the lack of solidification by the half-cut louvers. This showed that the theoretical approximations for the melting and solidification times were fairly accurate.

Table 9: Tabulated Results for the original Experimental protocol.

Evaluation	Expected Outcome	Result
Accuracy of Control System Response	10%	10%
Melting Time	(Hours) Quarter: 4 Half-Cut: 4.4	During California Spring (Approximately 80-85 °F Day) Start Time (7:00 AM Indoors) Quarter: 4.625 Hours Half: 5.875 Hours
Solidification Time	(Hours) Quarter-Cut: 8 Half-Cut: 10	During California Spring (Approximately 55-60 °F Night) Start Time (7:00 PM Indoors) Quarter: 8.0 Hours Half: Did not completely solidify, so 12+.
Overall Blind Coverage/Light Passage	10%	60%
Space Heating Capacity/Useable Thermal Energy	6000 kJ	48.90% percent decrease in energy consumption in the hutches. Amount of kWh was dependent on outdoor conditions.
Energy Savings	1.6668 kWh	
Consistent Daily Hutch Temperature Increase	3-5° Increase	Did not show a consistent results for temperature increase or decrease in the room during the day and night.
Calibration of Testing Environment	Equivalent Testing Environment	Environments were not equivalent, so experimental set-up was altered for comparison of the same hutch on different days with similar outdoor conditions.

The system shown in Figure 25 was originally designed for a different size window and, as such, was not the full system that we had expected to install as the top portion of the blind's structure was not installed. Since our team had to change our experimental set-up and continuously interchange the blind system between Hutch A and Hutch B, we had to let the system rest on a wood frame, which resulted in a larger space between the window and the blind system than we would have liked. The luminosity results showed that our blinds were letting a significant amount of light into the room for 60% of the daylight hours, whereas the cellular blinds completely blocked out the sun. This could have contributed to some loss of heat energy throughout our experiment, but the eventual mass production of this product would allow us to custom build a blind set for the window size and room conditions. Since the whereabouts of our blind system changed throughout the design process, we did not reach our goal of 20% blind coverage. Figure 25 also shows that there is a slight light passage between each louver. This allows for synchronized turning, but will have to be optimized to reduce that sun exposure if we want to have a marketable product.

Figure 25: The final blind set manufactured without the top portion to allow for ease of movement between hutches during testing.

Our team chose to compare our PCM blind system with cellular motorized shades, as these are currently the best product on the market in the same category as our system. The manufacturers' of cellular shades cite their ability to reduce heat gain and loss by acting as a barrier between the outside and inside of a window, but acknowledge that they do not emit energy. The cellular shades are also more expensive than our proposed benchmark price, and have a smaller theoretical R-value when compared to our system.

Using the experimental setup as described previously, our team ran the data logging system in Hutch A and B with nothing inside. This was done over daily periods in order to establish the brightness, indoor temperatures, and energy consumption of each hutch at varying outdoor temperatures. We then switched the PCM and cellular blinds between both Hutch A and B and continued data logging. Due to the complications we had with the inability to have equivalent testing environments, the results produced when the blind system was inside Hutch A were compared to the results from Hutch A with nothing inside, on days with similar maximum and minimum outdoor temperatures. The same comparison was done for Hutch B, and the cellular and PCM blind system were moved between Hutch A and Hutch B for variability. The location of each blind system on each day is tabulated in Table 12. Table 15 is color-coordinated to show the days that had similar outdoor temperatures and were used for comparison. As shown, none of the days were exactly the same and only the maximum and minimum outdoor temperatures were taken into consideration, rather than the varying temperatures throughout the day. The increased variability in the outdoor conditions made this the only option for comparison. More time, resources, and the possibility of a controlled environment would have solved this issue.

The results, summarized in Table 10 revealed that our blind system had an average reduction in energy consumption of 48.90%, whereas the cellular blinds only decreased energy consumption by 32.94% in the hutches. Since we were unable to factor in the effects of wind, humidity, and cloud cover and did not have enough data points to compare days that were exactly the same, assumptions had to be made to make these conclusions. These included the assumption that a hutch's results were suitable for comparison as long as the maximum and minimum outdoor temperatures were the same, or within a tolerance of $\pm$ 3°C. Although this outdoor temperature tolerance is high in comparison, it was necessary due to time constraints and the fact that we were forced to utilize the data points we had available. Based on the available energy in each louver, our team's estimated outcome was that it would produce 1.6668 kWh of heat energy. The magnitude of the energy production was dependent on the outdoor conditions so we chose to examine the percent decrease rather than an exact sum of what was produced with the 20% solidification of the blinds. With future testing, and by allowing the heater to run at a lower temperature, we may be able to eliminate heater energy consumption entirely and estimate an average kWh consumption for various outdoor nighttime temperature ranges.

Table 10: Summarized and average percent decrease in energy consumption when comparing the same hutch with and without a blind system on days with similar outdoor temperatures and the heaters running all day.

Experiment	Type	Comparison	Percent Decrease
2 (Hutch B)	PCM Blinds	7 (Hutch B)	28.54%
2 (Hutch A)	Cellular	7 (Hutch A)	16.21%
3 (Hutch A)	PCM Blinds	1 (Hutch A)	31.29%
3 (Hutch B)	Cellular	1 (Hutch B)	12.55%
4 (Hutch A)	PCM Blinds	1 (Hutch A)	65.77%
4 (Hutch B)	Cellular	1 (Hutch B)	45.45%
5 (Hutch B)	PCM Blinds	1 (Hutch B)	69.99%
5 (Hutch A)	Cellular	1 (Hutch A)	57.54%
Type		**Percent Decrease Average**	
PCM Blinds		48.90%	
Cellular		32.94%	

Regardless of the average result, the PCM blind system consistently resulted in a decreased heater energy consumption in comparison with the cellular blinds. Unfortunately, we were only able to conduct experiments during the spring in the California Bay Area, which was not optimum to establish the maximum energy benefits of our system. The use of our system is ideal for the winter when nights are much colder and heat is needed. Under these hot conditions, we saw that our blind system consistently melted the PCM mass 100% during the day, but only solidified the mass approximately 20% at night. We hypothesized that the experimental setup did not allow the PCM to completely solidify, since the heaters were set to such a high temperature. Unfortunately we were unable to set the heaters any lower because the hutches were experiencing high temperatures during the day and did not cool down far below the 75 degrees Fahrenheit. If the heaters were set to a lower temperature, and the room never cooled down to that low of a temperature, the heaters would not turn on and we would not have provided data for comparison in order for the team to establish results.

It is understood that by setting the heaters to such a high temperature, we might be overestimating our energy savings. For this reason, we would like to eventually have the ability to test the blind system during the fall and winter months and in a larger setting to establish the actual maximum output. For the remainder of the spring, we chose to modify the experimental setup by turning the heaters off and looking for trends in temperature rise and solidification of the mass at night. The results, accumulated in Tables 10 through 15 showed that the full set blind system almost completely solidified at night for the average 60° Fahrenheit indoor temperature. Unfortunately, we were only able to accumulate four data points and they were not consistent enough to establish concrete results. For this experiment, our PCM blind system was kept solely in Hutch B since Hutch A was known to reach extremely high temperatures and might provide us with unrealistic results. When comparing Hutch B with and without a blind system and with the heater turned off on days with as close to the same outdoor temperature conditions, we saw that our PCM Blind system actually had an average percent increase in room temperature of 12.55% during the day and a 9.25% percent decrease in room temperature at night, meaning that it did not keep the room cooler during the day and warmer at night in comparison to an empty hutch. As shown in Table 11 and stated previously, the days that were compared with each other did not have the exact same outdoor temperatures. The days for comparison were not accurate and the large amount of uncontrollable conditions proved this to be an unfavorable and failed experiment. The previous experimental setup also brought about many errors and potential for skewed data, but by turning the heater on allowed us to eliminate at least one more variable than the final temperature comparison experiment.

Table 11: Summarized and average percent increase between the indoor and outdoor temperature when comparing the same hutch with and without a blind system on days with similar outdoor temperatures and the heater was not running. It was observed that the louver set almost completely melted and solidified.

Experiment	Temperature Difference (°C) *		Type	Comparison	Temperature Difference (°C)*		Percent Increase**	
	MAX	MIN			MAX	MIN	MAX	MIN
10 (Hutch B)	0.95	2.42	PCM Blinds	9 (Hutch B)	0.46	6.59	107%	-63%
11 (Hutch B)	1.55	6.97	PCM Blinds	9 (Hutch B)	0.46	6.59	237%	5.7%
12 (Hutch B)	0.47	6.41	PCM Blinds	9 (Hutch B)	0.46	6.59	2.2%	-2.7%
12 (Hutch A)	8.7	10.99	Cellular	9 (Hutch A)	3.79	8.19	130%	34%
13 (Hutch B)	0.94	8.11	PCM Blinds	9 (Hutch B)	0.46	6.59	104%	23%
13 (Hutch A)	8.93	12.53	Cellular	9 (Hutch A)	3.79	8.19	136%	53%

Type	Average Temperature Difference		Average Percent Difference (In Comparison to Empty Hutch)	
	Maximum	Minimum	Maximum	Minimum
PCM Blinds	0.98	5.98	112.55%	-9.25%
Cellular	8.82	11.76	133.00%	43.5%

*Outdoor temperature subtracted from indoor temperature to produce a positive integer.
**Percent increase of the temperature difference between the outdoor and indoor temperature of the hutch containing the blinds from the empty hutch temperature difference on a day with similar outdoor temperature conditions.

Although we were unable to establish a completely controlled experimental set-up, and were limited on the number of data points we had to evaluate, our product had promising results that showed that it functioned as intended by decreasing the energy consumption of a heater at night. We did not have consistently in the results to establish that it increases room temperature at night and keeps it cool during the day, but future testing in a larger and controlled environment may help with establishing more concrete conclusions. Since we do know that the system is capable of fully melting and solidifying, even in the hot California summer conditions, we can then focus our experimental efforts on establishing whether the space between the blinds and the window is affecting the function of the system. It is necessary to prove that this function continues throughout the temperatures of the year in a variety of spaces. During the mass production stage, it would be optimum to develop an algorithm for room and window size, climate conditions, and user wants and needs to optimize a blind system for the user. Theoretically, our blind system has potential to emit 13,200 kWh, equivalent to $1375.78 savings in utility costs over 10 years in the average California home.[39,40,41] With future testing, in a controllable environment, we hope to determine the actual annual savings with our blind system.

[39] "Simple Interest Calculator - WebMath." WebMath - Solve Your Math Problem. N.p., n.d. Web. 8 May 2013. http://www.webmath.com/simpinterest.html.

[40] "Rates and Chart Tables - Electricity (2000 thru 2011)." California Public Utilities Commission . N.p., n.d. Web. 8 May 2013. <http://www.cpuc.ca.gov/PUC/energy/Electric+Rates/ENGRD/ratesNCharts_elect.htm>.

[41] "Clean Energy in My State: California Residential Energy Consumption." U.S. DOE Energy Efficiency and Renewable Energy (EERE) Home Page. N.p., n.d. Web. 8 May 2013. <http://apps1.eere.energy.gov/states/residential.cfm/state=CA#elec>.

Table 12: List of dates and conditions for experimental trials, including whether the heater was on and set to 75° Fahrenheit and whether a blind system was in either hutch or the blinds both had nothing in them for comparison.

Experiment	Date	Heater	Hutch A	Hutch B
1	May 16 - 17	Y	Nothing	Nothing
2	May 17 - 18	Y	Cellular	PCM Blinds
3	May 18 – 19	Y	PCM Blinds	Cellular
4	May 19 -20	Y	PCM Blinds	Cellular
5	May 20 – 21	Y	Cellular	PCM Blinds
6	May 21 – 22	Y	Nothing	Nothing
7	May 22 – 23	Y	Nothing	Nothing
8	May 23 – 24	N	Nothing	Nothing
9	May 24 – 25	N	Nothing	Nothing
10	May 25 – 26	N	Cellular	PCM Blinds
11	May 26 - 27	N	Cellular	PCM Blinds
12	May 28 - 29	N	Cellular	PCM Blinds
13	May 29 - 30	N	Cellular	PCM Blinds
14	May 30 - 31	N	Nothing	Nothing
15	May 31 – June 1	N	Nothing	Nothing

Table 13: Tabulated results for energy consumption by each hutches heater, and how much the PCM blind system melted and solidified when the heater was on and off in the hutch. Energy consumption was not monitored on days without the heater on, and melting and solidifying did not apply when the blind system was not installed in the hutch.

Experiment	Hutch A (kW-Hrs)	Hutch B (kW-Hrs)	Melt	Solidify
1	.815	1.023	N/A	N/A
2	1.272	1.287	100%	30%
3	.560	.892	100%	20%
4	.279	.558	100%	20%
5	.346	.307	100%	20%
6	.743	1.611	N/A	N/A
7	1.518	1.801	N/A	N/A
8	N/A	N/A	N/A	N/A
9	N/A	N/A	N/A	N/A
10	N/A	N/A	100%	80%
11	N/A	N/A	100%	80%
12	N/A	N/A	100%	90%
13	N/A	N/A	100%	95%
14	N/A	N/A	N/A	N/A
15	N/A	N/A	N/A	N/A

Table 14: Comparison of maximum and minimum temperatures throughout the days in both hutches. Since we were unable to build, configure, and orient the hutches so that they were equivalent we had to record all data for comparison to the same hutch on a different day.

Experiment	Hutch A Maximum Temperature	Hutch A Minimum Temperature	Hutch B Maximum Temperature	Hutch B Minimum Temperature
1	31.40	23.62	32.06	22.41
2	34.085	23.50	32.53	22.74
3	33.302	23.76	31.50	22.54
4	35.36	23.79	33.19	22.47
5	39.59	23.87	35.70	22.79
6	36.52	23.83	31.02	22.50
7	33.07	23.31	31.49	22.53
8	33.28	16.92	30.52	15.45
9	32.24	16.85	28.91	15.25
10	Lost Data	Lost Data	26.86	18.56
11	Lost Data	Lost Data	28.81	18.90
12	36.36	24.32	28.13	19.74
13	36.08	22.10	28.09	17.68
14	36.87	22.92	28.87	18.66
15	39.81	25.18	31.70	21.31

Table 15: Colored rows represent similar outdoor temperature conditions for comparison.

Experiment	Date	Heater	Maximum Outdoor Temperature	Minimum Outdoor Temperature
1	May 16 - 17	Y	28.54	13.06
2	May 17 - 18	Y	27.14	8.21
3	May 18 – 19	Y	28.64	10.985
4	May 19 -20	Y	33.96	11.62
5	May 20 – 21	Y	38.08	12.45
6	May 21 – 22	Y	28.11	8.67
7	May 22 – 23	Y	25.70	8.17
8	May 23 – 24	N	26.34	7.86
9	May 24 – 25	N	28.45	8.66
10	May 25 – 26	N	25.91	12.83
11	May 26 - 27	N	27.26	11.93
12	May 28 - 29	N	27.66	13.33
13	May 29 - 30	N	27.15	9.57
14	May 30 - 31	N	30.90	10.97
15	May 31 – 1	N	36.81	12.93

Chapter 7: Costing Analysis

Our team submitted proposals for grants to cover the original proposed expenses outlined in Table 16. We originally thought that the bulk of the project budget would go towards hardware and software, but the actual budget, shown in the Cost flow Spreadsheet of Appendix A.10 reveals that electronics for the final product and experimental equipment depleted majority of our funds. Table 16 outlines an initial overall expense total of \$11,270, whereas the Cost flow Spreadsheet reveals the actual expense total for the entire project at \$9,843.48. The original plan was that the cost of product integration into the Solar Decathlon Refract House, approximately \$8000, would be funded by a grant from the Lawrence Berkeley National Laboratory (LBNL). We also intended that the Fall Quarter, Second Louver Prototype (approximately \$3250) would be partially covered by a grant from the Center for Science, Technology and Society (CSTS). The remaining expenses and the single-louver prototype would also be covered by LBNL. Both organizations accepted our proposals, for a grant total of \$22,500. Originally, if any of the proposals fell through, we would have used funding provided by the Santa Clara School of Engineering. During the Spring Quarter, it was established that our blind system would be integrated into Kennedy Commons rather than the Refract House due to aesthetics and cost, so the initial budget proposed for that was transferred to integration into the new location. The final blind system built was for a 3-foot by 5-foot window. Longer blinds will be manufacturing upon completion of Fall and Winter time evaluation for the larger window in Kennedy Commons. Our team chose to overestimate costs for the various expenses in our original budget, and found that our overestimation was proven to be more of an exact amount. This taught us that every project will have complications, and fixing them requires time and money. Although our project had more complications that we hope to see in the future, a separate category in our budget should have been allotted for the potential issues in order to be truly accurate.

Clearly, in order to meet our team goal of creating a patentable and marketable project, the cost to manufacture our product must be much less than the price for which we sell it. In order to do this, we had to research the most efficient, yet cost-effective materials and hardware to be used for the project. Unfortunately, the prototype cost exceeded our goal price due to special orders and shipping costs. We used PCM purchased from Rubitherm Technologies, a German-based company, in our final system which increased the cost of the product greatly since the shipping costs were double the price of the actual product. When looking into mass production we would have to search for local PCM companies, or negotiate with Rubitherm to order mass quantities at a significantly cheaper price. Currently, there are only a few established phase change material companies in the United States including: Phase Change Energy Solutions located in Asheboro, North Carolina and Microtek Laboratories, Inc. in Dayton, Ohio, but unfortunately none have the variety of options that Rubitherm Technologies has. Rubitherm offers a variety of PCMs other than paraffin wax including eutectic salts, non-alkane, and inorganic metallics, and within the category of paraffin waxes there are a variety of melting temperatures and latent heat of fusions in order to optimize for a customer's window and room size, as well as environmental and weather conditions which is necessary to optimize our product for a larger market.

As shown in the Parts List Spreadsheet in Appendix A.9 the total cost of our final full-set prototype was $2167.42, far above our $800 goal for commercial sale. The majority of the cost was attributed to the Phase Change Material, whereas the hardware contributed to majority of the man-hours in production. In order to combat this large prototype cost, we hope to redesign some components for mass production. For example, the seven Top Blocks could be altered into an overall sheet rather than individual pieces. As expected, purchasing, manufacturing, and shipping individual components also increased the prototype cost dramatically. We could also combat the large prototype costs with the decision to look to supplies for the manufacture of our components, rather than purchasing our own capital equipment. Per Karl Ulrich and Steven Eppinger's *Product Design and Development*, the outlined cost of outsourcing components in larger quantities in Appendix B[42] would decrease our cost dramatically. Unfortunately, with these benefits the addition of an incoming and outgoing quality system, installation, and other employee expenditures arise. Further analysis is required in order to determine whether our product is marketable and capable of producing a profit.

[42] "Clean Energy in My State: California Residential Energy Consumption." U.S. DOE Energy Efficiency and Renewable Energy (EERE) Home Page. N.p., n.d. Web. 8 May 2013. <http://apps1.eere.energy.gov/states/residential.cfm/state=CA#elec>.

Table 16: Outline of initial budget for proposed expenses towards the louver waterproofing prototypes, single–louver control system prototype, and final full-set blind system product.

Proposed Expenses	
Louver Prototypes (Subtotal)	*$230.00*
PVC + Foil/Metallic	$50.00
(Reflective Material)	
Acrylic + Graphite Paint (Absorption Material)	$50.00
Misc. Blind Hardware	$100.00
CA Sales Tax (7.25%) & Shipping (Approximate)	$30.00
Second Window Shade Prototype (Subtotal)	*$3,220.00*
Paraffin Wax (PCM) – 5 kilos	$250.00
Blind Materials	
Reflective Material	$550.00
Absorption Material	$100.00
Misc. Blind Hardware	$400.00
Control System & Electronic Components	$1,000.00
Test Supplies	$500.00
CA Sales Tax (7.25%) & Shipping (Approximate)	$420.00
Solar Decathlon Integration (Subtotal)	*$7,820.00*
Paraffin Wax (PCM) - 15 kilos	$750.00
Multi-Walled Carbon Nanotubes (MWNTs) - 10 grams x 5	$1,250.00
Blind Materials	
Reflective Material	$550.00
Absorption Material	$250.00
Misc. Blind Hardware	$2,000.00
Control System & Electronic Components	$2,000.00
CA Sales Tax (7.25%) & Shipping (Approximate)	$1,020.00
Total Estimated Project Cost	**$11,270.00**

Chapter 8: Invention Disclosure Form Submission

Our team has completed and submitted an Invention Disclosure Form for a patent on our product, the initial submission can be found in Appendix A.8. Along with tracing and outlining all innovations developed within our design, we were to find competing technologies, including current solutions for the same problem, and to compare how much better our product is to that invention. We completed a Patent and Project search that can be found within the Invention Disclosure Form in Appendix A.8. The two major types of commercially released products on the market that shade and heat a home are window coverings and HVAC (Heating Ventilation and Air Conditioning) systems. Our invention differs in that it combines the heating and cooling benefits of both of these devices into one device. As shown below in the Patent and Project Search, the majority of devices invented store Phase Change Material in tanks or between glass windowpanes. The contrary to these patents and current technology are inventions that improve blind systems. Our invention seeks to reduce heating and cooling loads by shading and emitting heat energy at optimum times of the day, whereas current blind technology and patents seeks to provide a thermal barrier and change window characteristics similar to a wall in order to keep light and cooling or heat energy out of a room. A comparison of your product with each existing patent is included with the Patent Name, Number, and Abstract.

Chapter 9: Engineering Standards and Realistic Constraints

The goal of our project was to develop an innovative, operational, and safe product while maintaining high ethical standards in our team behavior, processes, and material selection. We decided it was imperative that we to examine the ethical consequences of each step and sub-system in our design process. The ethical issues that we determined were key in creating an ethical product were economic, social, sustainability, manufacturability, and health and safety. The primary ethic that our group sought to address was quality in research and workmanship for the user. As an ethical senior design team we made sure that we produced experimental results and manufactured products that were as high of quality as possible under the constraints of student work. We recognized that the quality of all decisions and processes made would have an impact on the ethical foundation of subsequent work, and would hopefully set a solid foundation for future teams. Those teams in turn have a responsibility to continue to produce high quality, ethically produced results.

Section 9.1: Economic

When preparing for the release of a product, one of the most important marketing decisions comes when it is time to set a price point for that product. Using the principles of supply and demand to set high prices for a particular product is generally legal, but can be unethical if it is pushed to an unreasonable level. Though our product most likely will not drastically affect the economy it would be our duty as the supplier of the product to provide the product at a reasonable price for those that need it if we were to go to market. After evaluating the manufacturing cost of our product, it was our team's hope to be able to produce a marketable product that could sell for a reasonable profit. Though it is the goal of many to make as much money as possible, gouging, or exorbitantly charging for goods, is an unethical process our team would never pursue. Another practice that our team would not feel comfortable pursuing, would be ensuring a warranty on the product shorter than the expected lifetime of the product. At the moment our product has an expected shelf life of 50+ years, but if instead of providing a lifetime warranty we were to provide a 10 year warranty we would be performing another legal, but unethical act. The owner of a product has the choice of warranty on a product, but using the knowledge of expected failure and not providing the customer service for potential harm or dissatisfaction is not something our team would feel comfortable pursuing.

Section 9.2: Social

We opted to focus on the needs of the customer/end-user when it came time to make any design decisions. We saw it as our duty to think about those who might directly or indirectly benefit from this line of research and the possible social benefits associated with it. In its simplest form, this project should produce a significant development in domestic space heating. This cheap, efficient method could benefit people in tropical and temperate regions across the world. Through several programs including Santa Clara's Frugal Innovations Lab, and EWB (Engineers Without Borders), we expect to be able to spread any developments made and perhaps several working copies of our design to communities in South America. In addition, if product development proceeds as planned, the blinds will be showcased in the Santa Clara's 2013 Solar Decathlon house, and seen by hundreds of thousands of visitors. This project can provide benefits to anyone at all with need for nighttime heating of their residential space; however, by working to keep the cost of the final product low, and by optimizing the design for the locals with hot, sunny days and cool nights, such as Northern Africa, we hope to provide a cheap, alternative to wood-burning fireplaces or inefficient electric space heaters. Additionally, the saved energy that these louvers offer can be earmarked to other more pressing energy concerns, such as water heating. We hope that the research and product design may also stem product and technological development to further improve health and quality of life by reducing energy consumption for society.

Section 9.3: Sustainability

Sustainability is defined as the designed product's extent to which it can continue to be used, as well as utilizing the world's resources effectively when designing the product. Our goal in order to be ethically sustainable was to develop a system with a life expectancy equivalent to simpler, commercially blinds. The benchmark selected for the shelf life of all of our individual materials was 50 years, and it was decided that the product should last at least 5 years without needing any repairs, and, when maintenance and repairs were needed, that they should be simple and inexpensive to implement.

We sought a product that could sustain a long life, far beyond the possible changes in design and style in society. In order to preserve resources and allow for sustainable economic practices to be developed around our product, we chose abundant materials, and looked into a variety of options to decrease the amount needed for each in our system. The assembly consisted of ABS, PCM, acrylic, steel, Delrin and aluminum parts, all of which are recyclable and have a shelf life beyond 50 years. The two major areas of concern were the acrylic and PCM. Per the specifications for RT 28HC, the paraffin wax utilized in our system, the wax's characteristics include several key characteristics for producing a sustainable final system. Some of these include the fact that it is a long-life product, provides constant performance over several ten thousands of cycles, and is non-toxic. One cycle is equivalent to one melt and solidification process, or the cycle that our blind system would pass through during the course of a 24-hour day. And, with a life of 10,000 cycles, the wax should function well for 27 years – well beyond the 5 year minimum no-maintenance period that we had established. Acrylic is also a sustainable, recyclable, and a long-life product but has the disadvantage of possibly experiencing distortion with continuous heating and cooling cycles. Therefore, should we mass-produce our product, we would opt to switch to a back painted glass surface to improve the overall life and sustainability of the system.

Section 9.4: Manufacturability

The manufacturing and research/experimentation processes posed some safety concerns for those involved. The manufacturing process for our design utilized a number of potentially dangerous machines and toxic chemicals, but the proper protocol was followed to mitigate risks, and there were not any cases noted in which there was either an injury, or an unnecessarily high risk.

Section 9.5: Health and Safety

Though typical blinds today do not pose an obvious threat to its users, many components of the automatic blind system could be potentially hazardous. As the developing and manufacturing engineering team it was our ethical duty to minimize those hazards. The United States Consumer Product Safety Commission's (CPSC) major concern in regards to window covering systems is the risk of cord strangulation. This concern is addressed with the American National Standard for Safety of Corded Window Covering Productions (ANSI/WCMA A.100.1), which focuses on the design and operation of continuous cord loops and chains, lift cord knots, and cord joiners. The US CPSC conducted a study between 1996 and 2005 that showed that 60% of cord system incidents were due to horizontal blinds, whereas the other 40% were caused by vertical. Our current blind design does not include a cord operating system, but we did take the aforementioned risks and statistics into consideration during our selection of vertically oriented louvers.

Any system needs safeguards to make sure it will be safe to sell to the public and meet any safety standards, such as IEC 60730, a major safety standard for household appliances. Our team analyzed several potential concerns, and found that the motor that would automatically control the rotation of the blinds, was cause for some concern over the possibility of a person or pet getting an appendage trapped between the louvers of our system. In order to address this, commercialization would include the development of a safety system to release the louvers when too much torque is applied, which would be an indicator that something or someone was trapped between the louvers. Another safety benchmark that we set for ourselves was the use of PCM that was non-toxic and not flammable, so a leak would not cause any harm. This was most important for families with children or pets, a significant portion of the potential customers interviewed for our customer needs assessment. Finally, we ensured that the control system was grounded so static would not build up in the insulation material and increase the probability of electric shock or fire.

Section 9.6: Environmental

Our team chose to review the potential benefits and harms involved in the mass commercialization and sale of our product, specifically those related to environmental concerns. The environmental benefits and drawbacks are outlined in Table 17, and focus on energy conservation and depletion, as well as sustainability of the materials selected for our product, outlined in previous sections.

Table 17: The potential positive and negative impact Phase Change Material in Automated Window Shades would have on the environment

Benefits	Drawbacks
Shades a window during the day to decrease air conditioning energy consumption.	Control system requires energy to run.
Warms a room at night to decrease Heater energy consumption.	Control system could utilize battery, which is not recyclable and will most likely end up in a landfill.
Primary materials used in the system are reusable, recyclable, or sustainably manufactured.	Increases potential for user harm than with traditional window blinds.

The most significant environmental benefit that our product provided was its ability to reduce or even eliminate the heating and cooling loads required by the average household. The most significant drawback of our product in terms of energy consumption was that the control system consumed energy in order to operate. The attached calculations assume an angular acceleration of 0.1 rad/s^2 and an angular velocity of 1 rad/s^2, and were done to show the effect that the specified acceleration and velocity conditions would have on the current drawn from our servo and Arduino microcontroller. For the hutch, five 36” quarter-cut louvers were used to cover a 3-foot by 4-foot window. The louvers had a maximum turn angle of 180° per day resulting in a need of 3.141 x 10^{-7} kWh to turn the louvers. When we applied the voltage input required to run the Arduino and servo motor we found that, to turn the blinds, the system required 2.512 x 10^{-8} mAh. Since the system ran every 15 minutes for 12 hours that represented a total current draw of 120.58 x 10^{-8} mAh per day. We would eventually like to combat this need for energy consumption – and the associated, but unsightly and inconvenient need to connect the system to a power source - by using solar power. Fortunately, the system only turns on every 15 minutes and therefore only requires small amounts of energy at infrequent intervals. Our team found a solar phone charger, seen in Figure 26 above, which is equipped with a 0.65 W solar panel and a 5000 mAh battery that is capable of 500 charge cycles[43]. Our Arduino microcontroller could easily be configured to have a USB input to utilize the 1 A maximum output current, which would exceed our energy need and would be best possible even for cloudy days.

Figure 26: Solar iPhone charge charger, connected via USB, to be utilized by our control system to avoid electrical plug-in and consumption.

The most important audience that was considered during the development process was the customer and end-user. It was our duty to consider those that might directly or indirectly benefit from this line of research and to determine the social benefit that our product might be able to produce. At the most basic level of social benefit, our project has produced developments in the possibilities for domestic space heating, making possible an efficient method of producing nighttime space heating with very little or no energy consumption that could benefit people in tropical and temperate regions across the world. Through several programs including Santa Clara's Frugal Innovations Lab, and EWB (Engineers Without Borders), we hope to be able to spread the lessons learned during our project so that we might be able to improve energy efficiency and quality of life across the world. This project has the potential to provide benefits to anyone with a need for nighttime heating of their residential space; however, by working to keep the cost of the final

[43] "Solar Iphone Charger | Rakuten.com | Solar Iphone Power Adapter."*Rakuten.com - Computers, Electronics, Digital Cameras, Books, DVDs, Music, Games, Software, Toys, Sports*. N.p., n.d. Web. 10 May 2013. <http://www.rakuten.com/th/solar-iphone-charger.html>.

product low, and by optimizing the design for the locals with hot, sunny days and cool nights, we sought to provide a cheap, alternative to wood-burning fireplaces or inefficient electric space heaters that would be particularly useful for people in developing countries. We could further improve the environmental impact by earmarking the energy saved by utilizing our system to other, more pressing energy concerns. We hope that our research and product design might also spur technological and product developments which will further improve the health and quality of life through the reduction in overall energy usage.

Chapter 10: Summary and Conclusions

The common goal of the team was to design and manufacture a marketable product that produces optimum results in terms of energy production, while meeting safety requirements and user concerns. We did this by optimizing all sub-systems via theoretical calculations and experimental testing and analysis. With evaluation of the Customer Needs Assessment, goals were set to complete our final system prototype reflecting as much feedback as possible. Our team focused on creating a safe, sleek, and low cost product by meeting the majority of the goals set on our Project Design Specification, informed by our Benchmark developed from existing systems on the market and patents. By accomplishing all set goals on time, and with a collaborative effort, we were able to submit a patent disclosure and complete evaluation of our product. Again, although we were unable to establish a completely controlled experimental set-up, our product resulted in a 48.90% decrease in heater energy consumption at night. Since we were unable to see a consistent increase in room temperature at night, testing in a larger and controlled environment is a possibility for future endeavors. Our team is currently working on integrating the final assembly into Kennedy Commons, as well as evaluating the product's ability for mass production and marketability. This will require further testing in the Fall and Winter, and design improvement.

Section 10.1: Overall Design Evaluation

The final system was designed with an intention to emphasize directional heat transfer. Though we knew that the final design was not the most aesthetically pleasing, this was not the main intent of the project. The intent was to alter the Trombe Wall (a wall that is filled with PCM, storing heat throughout the day and allowing the thermal energy to vacate the wall through either side). This strategy, obviously, is inefficient due to the multidirectional heat transfer during the nighttime hours. Our design was meant to use this stored thermal energy as efficiently as possible, reducing the entry of heat into the house during the day and reducing heat loss to the environment at night.

This worked very well, by utilizing materials that either emphasized conductivity or insulation properties, based on its desired placement on the louver. The ABS backing stayed fairly cool, compared to the thermally conductive acrylic facing. As far as the PCM was concerned, the Rubitherm product was very effective. At holding 245 kJ/kg while melting at 28°C, it would be difficult to find a phase change material that would be better suited for use in our system. The steel frame, though bulky and difficult to manufacture, was incredibly durable and extremely strong.

The one setback that we had with our design was the assembly of all the parts. The lack of professional machining (and the lack of care taken towards tolerances) resulted in a final system that did not fit together like it did in the Solid Works drawings. Files had to be taken to the steel frame to make space for the aluminum plates, which took about five man hours to complete. Once it was shaved down to size, however, the rack and pinion system worked nicely. However, the servo motor used for the final assembly had a faulty potentiometer, and would not function properly with the code, but would only perform a simple sweep of an angle. This did prove that the actuation system with the rack and pinion gears was working to satisfaction, and since the code and servo had already been proved to be functional, we believe that the system as a whole, when assembled with fully working parts, will function fully and correctly. In fact, once completed and turned manually, the system (complete with all seven quarter-cut louvers) was able to reduce nighttime heating costs by up to 35%. As far as our starting goals were concerned, these values were deemed exceptional, and our final design was deemed a success.

Section 10.2: Possible Variations and Modifications

While we tried to prototype early and often, and learned a great a lot from each of the three system prototypes that our team designed and manufactured, there were still a number of modifications that could be made to almost every component within our system.

Before addressing these modifications, however, it is relevant to note that the system may actually be better suited for applications other than a window in a residential space. The system performed as desired, but the poor aesthetic design of the system made it ideal for application in a wall, door, garage, skylight cover, pool cover, or any other device that could absorb solar radiation, and pass that energy to a building. All of the potential variations would be similar to the phase change material filled automated blind system that we have developed throughout the past academic year, but would be customized for use in these various other applications.

Our current louver design has been selected to optimize the volume to surface area ratio of the individual louvers while maintaining a high PCM volume to provide the required latent heat. However, our louver could potentially change in size or material depending on the optimized variable of choice. With new innovation that maximized the heat transfer through the wax from the front face of the louver to the back, the louver could be made deeper to increase thermal mass and storage.

Currently, the control system utilizes an Arduino microcontroller and simple C code to turn the louver to the desired angle from the spreadsheet, utilizing the compass to confirm that the base is placed in a known direction. In future iterations, the code could be written on a cheaper, smaller microcontroller, and the digital compass and clock could be built into this separate microchip. The options for control could increase as well, giving the user more options. Options could be added to turn the system on or off, or input a desired louver angle utilizing a touchscreen.

The actuation system can also be reduced in size and cost, while increasing potential efficiency. The current iteration was designed to be built in a college level machine shop, and was much stronger than necessary to accommodate changing louver sizes. The base could be built slimmer, lighter, and cheaper to manufacture with more customized and professional equipment. A more customizable motor could also be used in the future to reduce power consumption and noise.

Section 10.3: Lessons Learned

This experience has been an incredible introduction to engineering life after college. Working in a group environment, where the four mechanical engineers are responsible for every section of the project, was an experience that none of us had previously attempted. Though the engineering aspect itself was difficult, it was at least manageable, and we had anticipated the difficulty of these tasks. However, the budget delegation and managing of intra-team roles took a surprising amount of time to complete.

It was determined at the end of the project that we had procrastinated more than we thought we had. Towards the end of April and beginning of May, the team had to put in approximately 30 hour weeks to complete the base assembly and testing results by the start of the Senior Design Conference on May 9th due to a variety of complications, including changes to design and an in-equivalent test setup. If we had planned on this and worked on the assembly and calibration of testing environments in the earlier months of 2013, it would have been much more feasible to complete the project without working strenuously into the night.

Overall, the project taught the team members a lot about engineering in the “real world.” Good and bad, difficult and simple, this year long project was the most realistic, tangible product that we have made. We are very proud of our final product and the work that we put in to finish it.

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Appendices

Chapter A.1: Product Design Specification (PDS)

Design Project: Phase Change Material in Automated Window Shades
Team: Molten Moon Mechanical
Date: May 19, 2013
Revision: 05
Datum Description: See Footnotes

ELEMENTS/ REQUIREMENTS		PARAMETERS	
	UNITS	**DATUM**	**TARGET - RANGE**
PHASE CHANGE MATERIAL			
Melting Temperature/Point	°C	45[1]	25 – 35
Latent Heat	kJ/kg	180 – 220[2]	240 - 300
Melting Time	Hours	Quarter: 4.34 Half: 4.88	Quarter: 4
		Quarter: 8 Half: 10	Half: 4.5
Solidification Time	Hours	Quarter: 18.8	8
		Half: 21.2	10
Liquid Density	g/cm^3	0.78	0.78
Solid Density	g/cm^3	0.89	0.89
Space Heating Capacity/ Useable Thermal Energy per Louver	kJ	Quarter: 4283 (Theoretical)	Quarter: 4000
		Half: 8783 (Theoretical)	Half: 8000
Energy Savings per Hutch (16 Cubic Feet)	kWh	0.1562 (Theoretical)	0.15 (100%)
Volume Expansion	%	10	≤10**
Cost	US $/kg	~300	<300***
Toxicity	Severity Category	5[3]****	5

*N/A because there is no precedent for paraffin within a system similar to the one proposed.
**Via calculations. PCM properties less than the datum may not be attainable, but if found would allow for more material to be placed in the louvers because the expansion from solid to liquid has to be taken into consideration when filling each blind.
***We will purchase the best wax for our application, but at the most effective price.
****Needs to be a non-toxic material, this is the safest global classification of toxicity.

[1] Sharma, Atul, V.V. Tyagi, C.R Chen, and D. Buddhi. "Review on thermal energy storage with phase change materials and applications." *Science Direct* 1 (2007): 318-345.
[2] Ibid, Rubitherm Technologies.
[3] "Toxicity - Wikipedia, the free encyclopedia." *Wikipedia, the free encyclopedia*. N.p., n.d. Web. 1 Nov. 2012. <http://en.wikipedia.org/wiki/Toxicity>.

ELEMENTS/ REQUIREMENTS		PARAMETERS	
	UNITS	**DATUM**	**TARGET - RANGE**
CONTROL SYSTEM			
Energy Usage	kWh	N/A	< .5 kWh
Automatic Light and Temperature Readings	min	N/A	10
Adjustment of Blind Angle	min	N/A	10
Applied Torque	kg-cm	4.5[4]	Need to Calculate
LOUVER DESIGN			
Overall Volume Capacity (All Louvers)	m^3	N/A	> 0.041
Weight	kg	N/A	<22.680
Range of Motion	Degrees (Angle)	N/A	180
Accuracy of Response	%	N/A	10
Light Passage Through Window	%	N/A	10
Control System Response Time	Seconds	20u[5]	20u

[4] "43R Servo 360 Rotation Specification."*Spring RC*. N.p., n.d. Web. 1 Apr. 2013. <https://www.sparkfun.com/datasheets/Robotics/servo-360_e.pdf>.

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FINAL ASSEMBLY			
Price	US $	800[6]	<850
Cost	US $	N/A	<Price
Manufacturing Time	Hours/Per System	N/A	<24
Patents	Number to Attain	N/A	1
R-Value	R/ Thickness hr·ft2·°F/Btu	6.8[7, 8]	>6.6*****
Packaging	Mass of Recyclable Material	N/A	1/2 kg
Shipping Time	Business Days	Standard Shipping 4-8 Business Days	<5
Safety	# of Injuries Using Our Product per Year	12[9]	0
Weight	kg	N/A	<30
Shelf Life	Years	N/A	50+
Overall Blind Coverage (Hutch Window)	m^2	N/A	0.975
Consistent Daily Hutch Temperature Increase (Experiment in Comparison to Control)	°C	N/A	5

*****Datum R-Value is for an average double-pane window, and we hope to increase insulation with our blinds and crescent backside piece.

[6] Ibid, Menards.
[7] Ibid,Next Day Blinds.
[8] Ibid, R-Value Insulation Wikipedia.
[9] "Voluntary Standards - Window Blind Cords." CPSC Home Page | cpsc.gov . http://www.cpsc.gov/volstd/blindcords/blindcords.html (accessed October 29, 2012).

Chapter A.2: Concept Scoring Matrix

Project: Molten Moon Mechanical
System: Phase Change Material in Automated Window Shades
Date: 11/6/2012

	Criterion	1	2	3	4	5	6	7	8	9	10	11	12	SUM	FACTOR
1	Weight		1	0.5	0	0	0	0.5	0.5	1	1	0	0	4.5	4.5
2	Speed	0		0	0	0.5	0	1	0.5	1	1	0.5	0	4.5	4.5
3	Adjustment Accuracy	0.5	1		0	0.5	0	1	1	1	1	0.5	0.5	7	7
4	Safety	1	1	1		1	1	1	1	1	1	1	1	11	11
5	Price	1	0.5	0.5	0		0	0.5	0.5	1	1	0.5	0	5.5	5.5
6	Cost	1	1	1	0	1		1	1	1	1	1	0.5	9.5	9.5
7	Manufacturing Time	0.5	0	0	0	0.5	0		0.5	1	1	1	0	4.5	4.5
8	Patents	0.5	0.5	0	0	0.5	0	0.5		1	1	0.5	0	4.5	4.5
9	Packaging	0	0	0	0	0	0	0	0		0.5	0.5	0	1	1
10	Shipping Time	0	0	0	0	0	0	0	0	0.5		0	0	0.5	0.5
11	R-Value	1	0.5	0.5	0	0.5	0	0	0.5	0.5	1		0	4.5	4.5
12	Aesthetics	1	1	0.5	0	1	0.5	1	1	1	1	1		9	9

Fill in upper triangle of the matrix

Working across each row, determine if the criterion in that row is more important (1), same importance (0.5) or less important (0) than the criterion in that column

Chapter A.3: Quality Function Deployment Matrix

Design Project = Molten Moon Mechanical   System= Phase Change Material in Auto

	TARGET or	DESIGN IDEAS																	
CRITERIA	FACTOR	1 = Baseline		Bevel Gears		Drive Screw		Belt		Actuation Rod		Crank/lever		Gear and rail					
Time – Design	1	1		2		1		2		1		2		4					
Time – Build	1	1		1		3		2		3		2		2					
Time – Test	1	1		0.5		1		2		4		2		1					
Time Score	10		10		11.67		16.67		20.00		26.67		20.00		23.33		0.00		0.00
Cost – Prototype	5	$ 1.00		$ 2.00		$ 2.00		$ 2.00		$ 5.00		$ 4.00		$ 4.00					
Cost – Production	9.5	$ 3.00		$ 3.00		$ 3.00		$ 4.00		$ 6.00		$ 5.00		$ 5.00					
Cost Score	10		2.57895		3.58		3.58		4.11		8.16		6.63		6.63		0.00		0.00
Weight	4.5	3	13.5	1	4.5	4	18	5	22.5	1	4.5	2	9	3	13.5		0		0
Speed	4.5	3	13.5	4	18	2	9	1	4.5	1	4.5	4	18	4	18		0		0
Adjustment Accuracy	7	3	21	2	14	4	28	1	7	3	21	3	21	2	14		0		0
Safety	11	3	33	1	11	2	22	4	44	2	22	1	11	1	11		0		0
Price	5.5	3	16.5	5	27.5	4	22	4	22	3	16.5	5	27.5	5	27.5		0		0
Cost	9.5	3	28.5	5	47.5	3	28.5	5	47.5	4	38	4	38	4	38		0		0
Manufacturing	4.5	3	13.5	2	9	2	9	3	13.5	2	9	3	13.5	3	13.5		0		0
Patents	4.5	3	13.5	3	13.5	6	27	2	9	3	13.5	2	9	7	31.5		0		0
Packaging	1	3	3	3	3	3	3	7	7	1	1	2	2	2	2		0		0
Shipping Time	0.5	3	1.5	3	1.5	1	0.5	5	2.5	1	0.5	5	2.5	3	1.5		0		0
R-Value	4.5	3	13.5	3	13.5	2.5	11.25	3	13.5	1	4.5	2	9	1	4.5		0		0
Aesthetics	9	3	27	3	27	3	27	2	18	1	9	1	9	3	27		0		0
	TOTAL		198.0		187.3		197.6		199.5		121.8		155.4		184.6		12.6		12.6
	RANK																		
	% MAX		99.3%		93.9%		99.1%		100.0%		61.0%		77.9%		92.6%		6.3%		6.3%
	MAX	199.5																	

NOTE: User fills in Purple areas, gold areas are calculated or fixed
Light blue areas filled from prioritizing matrix

BASELINE =

Design Idea Descriptions

2	two
3	three
4	four
5	five
6	six
7	seven
8	eight
9	nine
10	ten

Timescore(i)=Timescore(B)*(TD(i)/TD(B) + TB(i)/TB(B) + TT(i)/TT(B))/3
Costscore(i)=Costscore(B)*(Cprot(i)/Cprot(B) + Cprod(i)/Cprot(B))/2
Total(i) = SUM(Factor(j)*Comparison(i,j)) + (Timescore(B)-Timescore(i)) + (Costscore(B) - Costscore(i))

Comparison(i,j) = 5 if idea i is much better than baseline for criteria j
Comparison(i,j) = 4 if idea i is better than baseline for criteria j
Comparison(i,j) = 3 if idea i is same as baseline for criteria j
Comparison(i,j) = 2 if idea i is worse than baseline for criteria j
Comparison(i,j) = 1 if idea i is much worse than baseline for criteria j

Chapter A.4: Customer Needs Raw Data

Potential Users/Customer Interviews

Due to time constraint and the desire to receive input from a variety of customer demographics, some of the customers were interviewed personally, on the phone, and others by email questionnaire. Each individual was provided with a brief overview of the product for context and then asked the questions listed below. The questions were open-ended and constructed for an interview typesetting, which proved to be true since we received our best feedback from the interviews compared to the questionnaire. The customer demographics and references are also listed and their responses are listed in Appendix 1.

Interview and Email Questionnaire

Brief Product Overview: We are developing automated window blinds filled with phase change material to store the sun's energy and heat a home at night, while shading and keeping it cool during the day. The design will consist of a control system that will operate the blinds so that they switch position throughout the day, depending on the temperature, brightness, and motion of the sun in the outside environment. Overall, our product will provide an economic and sustainable energy source for the world and could potentially be optimized for a variety of weather conditions.
Demographic Questions: Age and Gender

1. What rooms in your home/building would you be interested in having a permanent, partially blocked window, where the room is shaded during the day and heated at night? Would you rather have a partially blocked skylight or window in your home?
2. How much money would you be willing to spend on a blind system that would cut the cost of nighttime heating? Factoring in that it would eliminate the current cost of approximately 10 Cents per kWh to heat your home, totaling about $100 per year per room for an average home.
3. Would you be willing to manually adjust blinds approximately 3 to 4 times a day to cut the cost of the blinds and increase the amount of heat to your room? Or would you prefer and be willing to pay for an automatic system with smaller energy production?
4. What is aesthetically important to you for a built-in system? (Size, Material, Colors, etc.)
5. Overall, do you think you would be interested in blinds that diminish the need for space heating, even though they are built-in and do not fold away like typical blinds? Why or why not?
6. Do you have any concerns about the safety?
   How much time would you be willing to spend to set-up the product?
   What type of lifetime/shelf-life would you expect the product to withstand?
   What is the typical maintenance of your ordinary blinds and what is a reasonable maintenance for this product (Maximum Cleaning Time)?

Any other comments on the potential product.

Solar Decathlon Interiors Team

Avon, Beth. Interview by author. Written Questionnaire. Email, October 13, 2012.

Team Lead for Solar Decathlon Interiors, Female, 20

1. The bedroom, I think that natural light is very important, and most people do not spend much time during the day in their bedrooms.
2. Custom blinds are typically between $75 and $300. I would pay up to $500 for the blinds.
3. Yes, people typically adjust their blinds in their home, so I don't seeing it as being an issue.
4. The material and the color, I want them to appear to be part of the aesthetic of the home, not just part of the thermal system.
5. Yes, as long as they could allow light into the room, or block light out depending on what is necessary.

Karasek, Kathryn. Interview by author. Written Questionnaire. Email, October 15, 2012.

Member of Solar Decathlon Interiors Team, Female, 19

1. Office or bedroom - really any room facing west. I'd rather have a blocked window than skylight.
2. I would probably be willing to spend around $200-500 because I would likely not be living in a house for a shorter period of time than 2-5 years.
3. I'd rather have an automated system because it is likely that I will not be at home during most of the day.
4. Aesthetically, the blinds just couldn't look too bulky. They should look fairly sleek and consistent with the other window covering in the house.
5. Yes, because any cost saving is worth the learning curve of operating new blinds.

Fitzpatrick, Joseph. Interview by author. Written Questionnaire. Email, October 17, 2012.

Member of Solar Decathlon Interiors Team, Male, 18.

1. I think I wouldn't want the blinds in the kitchen or bedroom just cause I like being able to see the windows while in there.
2. As long as the blinds save me money in the long run I'd be willing to spend $50 to $200 probably on it.
3. If I was home most of the time I'd be willing to adjust them manually, I'd rather not have to spend more money on making it automatic and losing efficiency because to me that is the big selling point. And if they are easy to adjust that'd be a bonus.
4. The most important part aesthetically to me is that it blends in and doesn't look too out of place, so I don't know if to match the color or have a good contrasting one. And the smaller the better I think.
5. I'd think id be interested in the blinds because space heaters don't look that good to me. I'm kind of confused as to what these blinds are; does it cover half the window and not move?

Homeowners/Apartment Residents

Nash, Lauren. Interview by author. Personal interview. San Jose, CA, October 19, 2012.

Homeowner, Female, 52

1. Bedroom, Skylight, Bathroom

Not Living Room, Dining Room, or Kitchen because I do not want an obstructed view of my front and back yard.

2. Maximum $100
3. Covered hardware, not bulky, a variety of color options at least white or natural wood.
4. No, I want automated blinds because I am not home during the day.
5. Yes, but in particular rooms. I like innovative products like this as long as there is research and support to prove that the product works.
6. What is the expected lifetime for this product to work? I would want it to be as long as possible if I am making an investment by purchasing them. I would expect to get at least 5 years out of the product since I do not redecorate a room that often.

Are there any risks/hazards with the wax or the electronic system? Would they be safe if a baby were to hit/play with them?

What geographic areas are you targeting for this product? I would think that the west coast and certain areas around the world would have the correct weather conditions for this product.

Make as cheap as possible, because it is actually saving energy bills for half of the year. The other half it is hot and I like a cool room during the summer.

Logan, Austin. Interview by author. Written Questionnaire. Email, October 17, 2012.

Apartment Resident, Male, 21

1. Bathroom and Bedroom, I'd prefer a skylight to be covered.
2. Less than $100.
3. I'd pay for the automatic system.
4. Tan, White, Light Colors, Bamboo or Wood Textures
5. Yes, because they are multi-versatile.
6. Are each of the surfaces easy to clean and could I use normal housecleaners (409, Windex, etc.) and items (Swiffer, Feather Duster, Paper Towels, etc.) to clean them? I typically clean by blinds once a month and probably would not do any more than that for these blinds as well.

Can you make the automatic system so that you can manually adjust the blinds as well if you wanted to turn them a specific way at a certain time?

How long does the wax only last for? I would want the product to last for many years since that is what I get out of my blind and space heating system now. Between 8 to 10 years.

Can you easily set them up and if something were to break can it be replaced or do you have a service to fix the blind. Does the wax make the blinds heavy and would that increase shipping cost?

Becks, Theresa. Interview by author. Phone interview. San Jose, CA, October 12, 2012.

Homeowner, Female, 53

1. Bathroom, Garage, Office.
2. I would pay up to $100 per set.
3. I would want the automatic system that is too much upkeep.
4. Natural colors that would match the other accents in my room. I have white wood blinds right now and would probably want the same for this product.
5. Yes.
6. I clean my blinds every week and would do the same for these blinds but not anymore than that. I use Windex and a paper towel. Would these blinds need a special product to be used to clean them?

For the blinds that are floor length my dogs often run through them, would that be safe for them? Same for my grandsons that come to visit.

How are the sensors powered? Will I have to change a battery often?

McKay, Riley. Interview by author. Written Questionnaire. Email, October 14, 2012.

Apartment Resident, Female, 21

1. Guest bedrooms, potentially master/kid's bedrooms, living room, computer/entertainment room.
2. Upwards of $1,000.
3. I would want an automatic system that would be installed for me.
4. Being able to match the system with the furnishings that are in my home already. Also having a system that is not extremely noticeable/will attract too much attention away from the room itself.
5. Yes.
6. If it is $1,000 + installation, I would expect the product to last (in my home) for many years 10+.

The cleaning time that is spent on the blinds in my home now is about an hour every 2-3 weeks.

Zatopa, Michael. Interview by author. Written Questionnaire. Email, October 21, 2012.

Homeowner, Male, 59

1. One bedroom that gets pretty warm on sunny days, and cool on cooler days. More likely a skylight than window.
2. If that's the entire savings from doing that to the entire house, I would be very hesitant if these were substantially more than normal high quality wood blinds or shutters. The savings does not seem enough to compensate particularly from the loss of views to the outside, and not being able to adjust the blinds.
3. Assuming that these adjustments would only be to the sides of the house where the sun shines, and the blinds are reasonably attractive, and actually can be adjusted to allow views outside, this is a reasonable trade off.
4. The most important aesthetic issue is the view looking outside, and privacy from the outside particularly at night

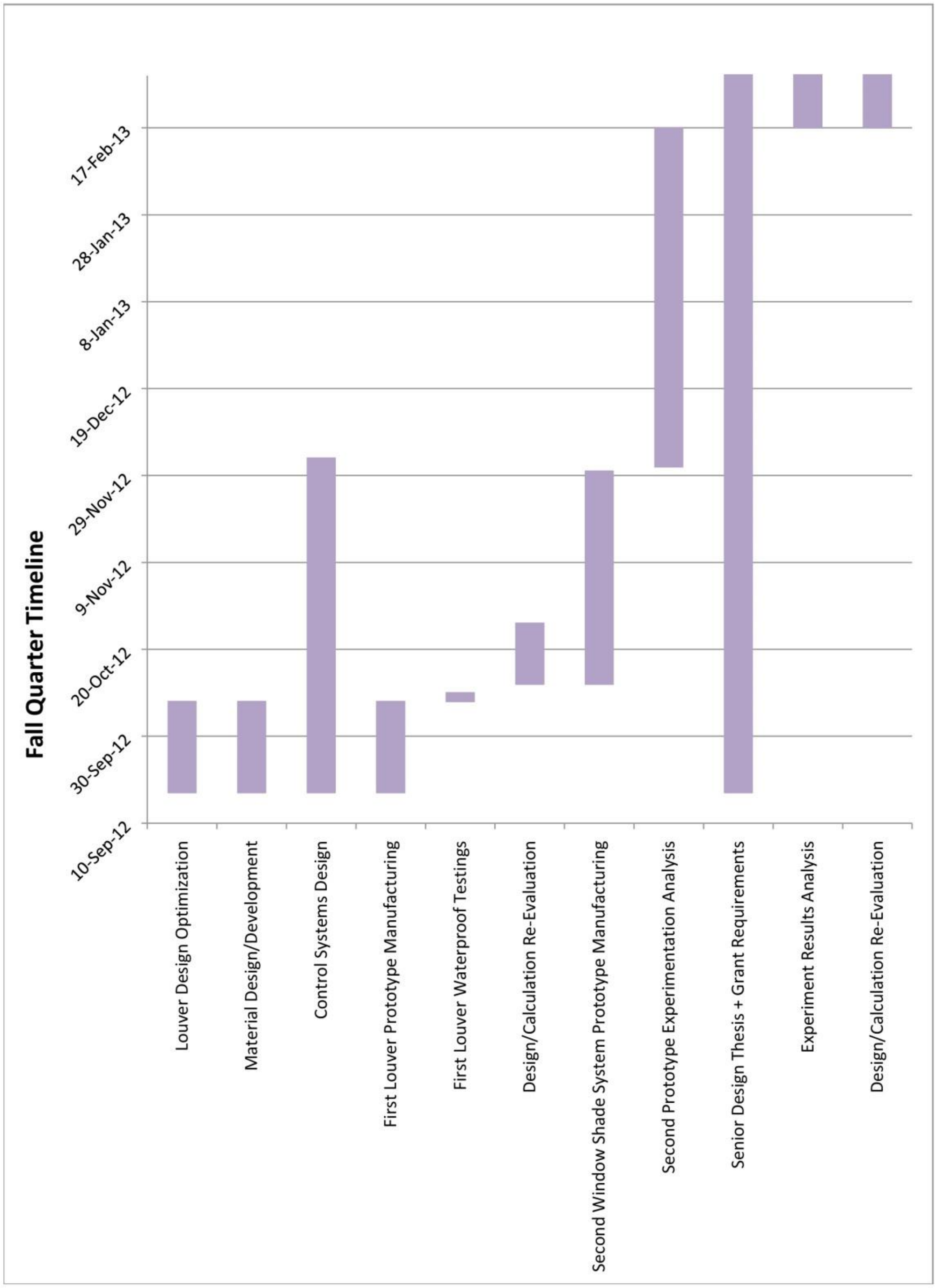
when lights are on inside. The other cosmetic issues would be similar to wood or Levelor style blinds, generally using white or off-white.
5. This is an issue of conservation vs. cosmetics/function. If the blinds prevent seeing out of the window, and that can't be changed, I would be hesitant to do this, except possibly in a couple of key places facing the sun. Privacy is also a concern.
6. It would make the most sense if these blinds function similar to wood shutters or wide Levelor style wood blinds, so that if there is no sun shining on that window, the blinds can be straighten parallel to the ground so they can reveal the most view from the outside. Otherwise, the house feels cave like. Also, cost should be competitive with faux wood shutters, which are not inexpensive. But if too costly, it is unlikely many homes would buy them.

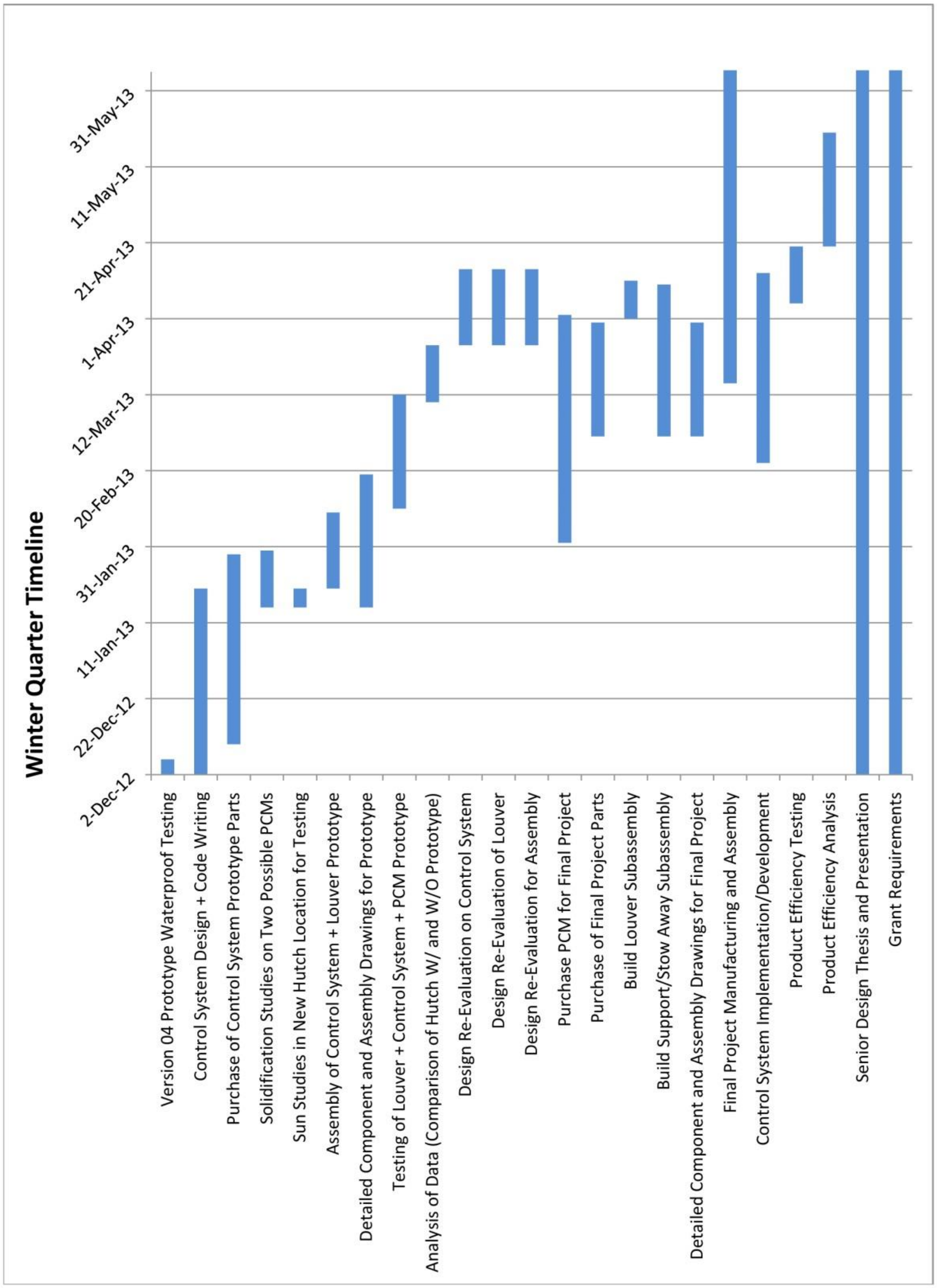
Gallau, Marion. Interview by author. Written Questionnaire. Email, October 21, 2012.
Homeowner, Female, 51
1. In our home the dining room and the upstairs bedrooms could be partially blocked. I would rather a window be blocked. I have heard too many issues surrounding skylights to be interested in installing any in our home.
2. Up to $500 per window with the assumption that the blinds would last a certain period of time.
3. Manually adjusting the blinds would not be an issue for me. Currently I open and close blinds depending on the time of day. I doubt I would pay for an automated system.
4. All of the above. I try to look at every facet of a project before moving forward.
5. Yes, I would be interested. I would love to reduce me heating (gas) portion of my PGE bill. Perhaps not on every window as I like to allow in maximum light at certain times, i.e. for houseplants
6. Any blinds that I would purchase would have to be aesthetically pleasing to look at and flow with my current home design.

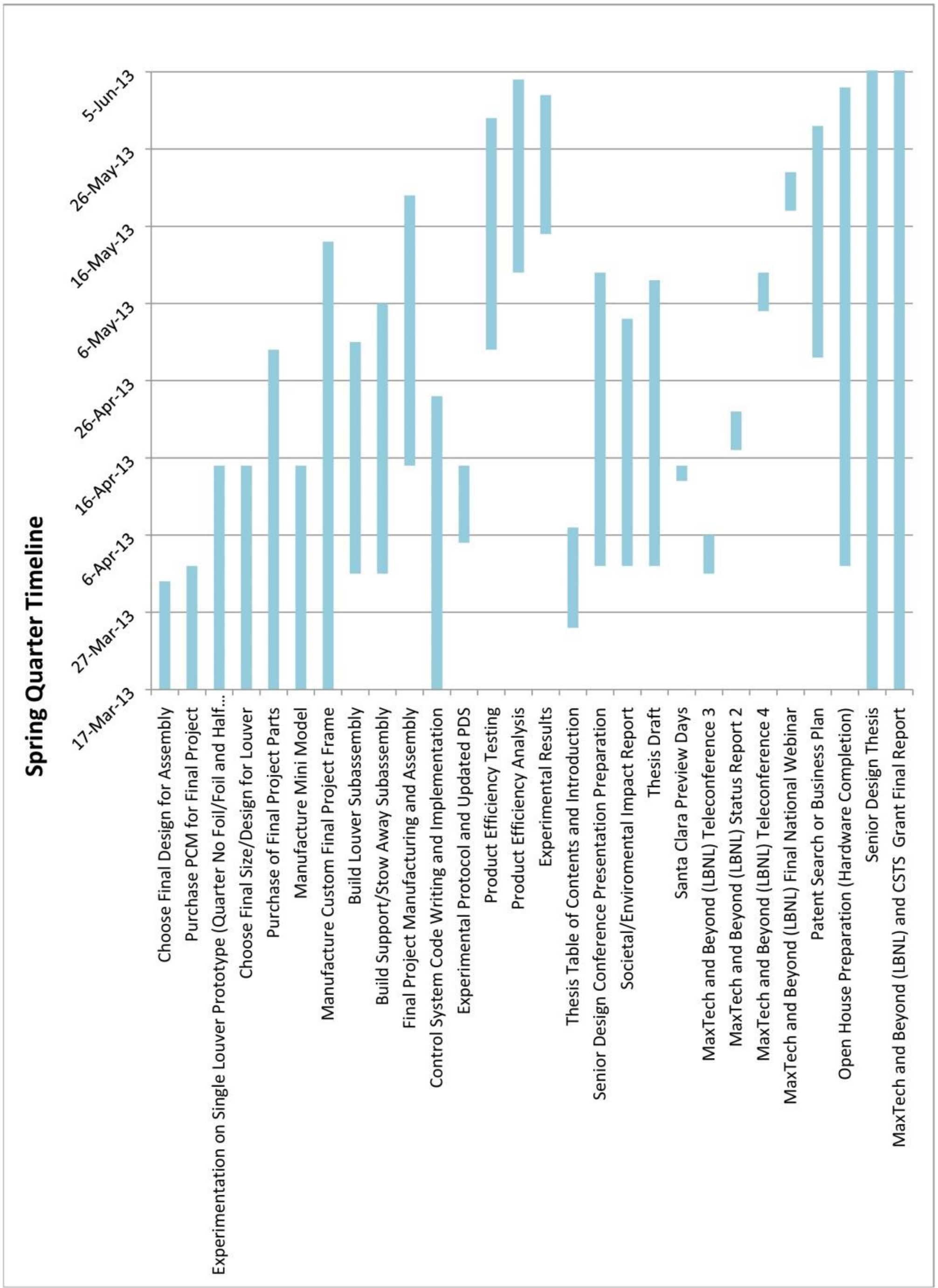
Managers within a Corporate Business Park
Durocher, Christopher. Interview by author. Personal interview. Fremont, CA, October 18, 2012.
Manger within a Corporate Business Park.
Solar Homeowner.
Male, 50
1. Install in 3 south facing rooms with one window each. Blocked windows are acceptable – currently have solid wood shutters installed.
2. $500 per window.
3. Manual adjustment is not an option – no one is home during the day. An automated system would be acceptable if solar panels were installed in order to offset the daytime usage.
4. Safety and Material
5. Yes, I would be interested in an installation in order to reduce my PGE bill.

Nash, Lauren. Interview by author. Personal interview. San Jose, CA, October 19, 2012.
Manger within a Corporate Business Park, Female, 52
Interview Feedback: These could potentially be used in areas that would require nighttime heating because there are bodies in those rooms. A manufacturing floor (non-clean room setting), call-centers, security. It might not be beneficial in office areas where light is necessary in order to keep employees awake and motivated, and often don’t stay late and long enough to require nighttime heating from sunset to sunrise.

Chapter A.5: Quarterly and Yearly Timelines




Winter Quarter Timeline
2-Dec-12
22-Dec-12
11-Jan-13
31-Jan-13
20-Feb-13
12-Mar-13
1-Apr-13
21-Apr-13
11-May-13
31-May-13
Version 04 Prototype Waterproof Testing
Control System Design + Code Writing
Purchase of Control System Prototype Parts
Solidification Studies on Two Possible PCMs
Sun Studies in New Hutch Location for Testing
Assembly of Control System + Louver Prototype
Detailed Component and Assembly Drawings for Prototype
Testing of Louver + Control System + PCM Prototype
Analysis of Data (Comparison of Hutch W/ and W/O Prototype)
Design Re-Evaluation on Control System
Design Re-Evaluation of Louver
Design Re-Evaluation for Assembly
Purchase PCM for Final Project
Purchase of Final Project Parts
Build Louver Subassembly
Build Support/Stow Away Subassembly
Detailed Component and Assembly Drawings for Final Project
Final Project Manufacturing and Assembly
Control System Implementation/Development
Product Efficiency Testing
Product Efficiency Analysis
Senior Design Thesis and Presentation
Grant Requirements


Spring Quarter Timeline
17-Mar-13
27-Mar-13
6-Apr-13
16-Apr-13
26-Apr-13
6-May-13
16-May-13
26-May-13
5-Jun-13
Choose Final Design for Assembly
Purchase PCM for Final Project
Experimentation on Single Louver Prototype (Quarter No Foil/Foil and Half...
Choose Final Size/Design for Louver
Purchase of Final Project Parts
Manufacture Mini Model
Manufacture Custom Final Project Frame
Build Louver Subassembly
Build Support/Stow Away Subassembly
Final Project Manufacturing and Assembly
Control System Code Writing and Implementation
Experimental Protocol and Updated PDS
Product Efficiency Testing
Product Efficiency Analysis
Experimental Results
Thesis Table of Contents and Introduction
Senior Design Conference Presentation Preparation
Societal/Enviromental Impact Report
Thesis Draft
Santa Clara Preview Days
MaxTech and Beyond (LBNL) Teleconference 3
MaxTech and Beyond (LBNL) Status Report 2
MaxTech and Beyond (LBNL) Teleconference 4
MaxTech and Beyond (LBNL) Final National Webinar
Patent Search or Business Plan
Open House Preparation (Hardware Completion)
Senior Design Thesis
MaxTech and Beyond (LBNL) and CSTS Grant Final Report

Chapter A.6: Louver Size Optimization Excel Sheet

Nom. Pipe Size

Nominal Pipe Size (Inches)	Outer Diameter (Inches)	Average Inner Diameter (Inches)	Outer Radius (Inches)	Average Inner Radius (Inches)
2	2.375	2.047	1.1875	1.0235
3	3.5	3.042	1.75	1.521
4	4.5	3.998	2.25	1.999
5	5.563	5.016	2.7815	2.508
6	6.625	6.031	3.3125	3.0155
8	8.625	7.942	4.3125	3.971
10	10.75	9.976	5.375	4.988
12	12.75	11.889	6.375	5.9445
q (Degrees)	q (Radians)			
90	1.571			
rliquid (g/cm3)	rsolid (g/cm3)	hsl (Joules)		
0.78	0.89	180		

1

2-Inch

Increments of 0.1 inches.
*See attachment for calculations.

	rINNER (Height of Triangulai Portion)	hINNER (Height of Arced Portion)	rINNER/RI	cos-1 (r/R)	theta (Central Angle [Radians]	theta (Central Angle [Degrees]	sin (theta) [Radians]	sin(theta) [Degrees]	AID (square inches [radians])	rOUTER	R2OUTER - r2OUTER	SQRT (R2OUTEF - r2OUTER)	aOUTER (Chord Length)	rINNER	R2INNER - r2INNER	SQRT (R2INNER - r2INNER)	aINNER (Chord Length)
RINNER	0.9235	0.1	0.9022960	0.4457303	0.8914606	51.076934	0.7779902	44.575560176	0.0594330833	1.0714765510	0.2620942	0.5119514	1.0239028	0.9235	0.1947	0.4412482	0.8824964
1.0235	0.8235	0.2	0.8045920	0.6358081	1.2716162	72.858241	0.9555784	54.750612639	0.1655330254	0.9554531021	0.4972656	0.7051706	1.4103412	0.8235	0.3694	0.6077828	1.2155657
ROUTER	0.7235	0.3	0.7068881	0.7857073	1.5714146	90.035428	0.9999998	57.295768559	0.2992934633	0.8394296531	0.7055141	0.8399488	1.6798977	0.7235	0.5241	0.7239475	1.4478950
1.1875	0.6235	0.4	0.6091841	0.9157648	1.8315297	104.93892	0.9662011	55.359248650	0.4532384738	0.7234062042	0.8868397	0.9417216	1.8834433	0.6235	0.6588	0.8116649	1.6233299
DINNER	0.5235	0.5	0.5114802	1.0338898	2.0677796	118.47504	0.8790248	50.364413292	0.6226413898	0.6073827552	1.0412424	1.0204128	2.0408257	0.5235	0.7735	0.8794884	1.7589769
2.047	0.4235	0.6	0.4137762	1.1441981	2.2883962	131.11544	0.7533861	43.165844260	0.8040016880	0.4913593063	1.1687222	1.0810745	2.1621491	0.4235	0.8682	0.9317725	1.8635450
DOUTER	0.3235	0.7	0.3160723	1.2492096	2.4984192	143.14888	0.5997377	34.362443356	0.9944840436	0.3753358573	1.2692792	1.1266229	2.2532458	0.3235	0.9429	0.9710303	1.9420607
2.375	0.2235	0.8	0.2183683	1.3506541	2.7013083	154.77356	0.4261966	24.419270278	1.1916491838	0.2593124084	1.3429133	1.1588413	2.3176827	0.2235	0.9976	0.9987992	1.9975985
	0.1235	0.9	0.1206643	1.4498371	2.8996743	166.13910	0.2395654	13.726090416	1.3933015410	0.1432889594	1.3896245	1.1788233	2.3576467	0.1235	1.0323	1.0160216	2.0320433
	0.0235	1	0.0229604	1.5478338	3.0956677	177.36869	0.0459087	2.6303778405	1.5973909533	0.0272655105	1.4094128	1.1871869	2.3743738	0.0235	1.047	1.0232301	2.0464603

Horizonta Blinds L = 3' = 36"	VID (cubic inches [radians])	aOUTER (Chord Length)	Window Height/aC	Number of Blinds Required	Number of Blinds for Available Energy	VTOTAL (cubic inches [radians	Available Energy per Louver (KJ/louver)	Available Energy of All Louvers (KJ)	Available Energy of All Louvers (kWh)	Blackbody Surface Area	sINNER	Reflective Surface Area	Total Surface Area	Available PCM Mass	Mass/Tota Surface Area	Mass/Blac Surface Area	Mass/Refle Surface Area
Outer Diameter (Inches)	2.1395909	1.0239028	82.039035	83	82	175.44646	4.9226314713	403.65578064	0.1121355758	31.769872	0.9124100	32.846760	64.616632	136.84824	2.1178485	4.3074847	4.16626293
2.375	5.9591889	1.4103412	59.560052	60	59	351.59214	13.710513321	808.92028598	0.2247180554	43.760365	1.3014991	46.853970	90.614336	274.24187	3.0264733	6.2669008	5.85311917
	10.774564	1.6798977	50.003043	51	50	538.72823	24.789415916	1239.4707958	0.3443249870	52.124220	1.6083429	57.900345	110.02456	420.20802	3.8192199	8.0616652	7.25743555
	16.316585	1.8834433	44.599164	45	44	717.92974	37.540135058	1651.7659425	0.4588605788	58.439876	1.8745707	67.484546	125.92442	559.98519	4.4469943	9.5822446	8.29797677
	22.415090	2.0408257	41.159809	42	41	919.01869	51.571177687	2114.4182852	0.5873853996	63.323171	2.1163724	76.189409	139.51258	716.83457	5.1381357	11.320257	9.40858563
	28.944060	2.1621491	38.850233	39	38	1099.8743	66.592607867	2530.5190989	0.7029782056	67.087620	2.3421736	84.318249	151.40587	857.90196	5.6662397	12.787783	10.1745703
	35.801425	2.2532458	37.279553	38	37	1324.6527	82.369585699	3047.6746708	0.8466440235	69.914187	2.5571321	92.056756	161.97094	1033.2291	6.3791017	14.778533	11.2238272
	42.899370	2.3176827	36.243096	37	36	1544.3773	98.700074878	3553.2026956	0.9870797088	71.913548	2.7647891	99.532407	171.44595	1204.6143	7.0262043	16.750867	12.1027347
	50.158855	2.3576467	35.628747	36	35	1755.5599	115.40222432	4039.0778513	1.1220558271	73.153559	2.9678167	106.84140	179.99496	1369.3367	7.6076393	18.718662	12.8165366
	57.506074	2.3743738	35.377747	36	35	2012.7126	132.30622640	4630.7179241	1.2864134393	73.672572	3.1684159	114.06297	187.73554	1569.9158	8.3623791	21.309366	13.7635884

Vertical Blinds L = 7' = 84"	VID (cubic inches [radians	aOUTER (Chord Length)	Window Height/aC	Number of Blinds Required	Number of Blinds for Available Energy	VTOTAL (cubic inches [radians	Available Energy per Louver (KJ/louver)	Available Energy of All Louvers (KJ)	Available Energy of All Louvers (kWh)	Blackbody Surface Area	sINNER	Reflective Surface Area	Total Surface Area	Available PCM Mass	Mass/Total Surface Area	Mass/Black Surface Area	Mass/Reflect Surface Area
Outer Diameter (Inches)	4.9923789	1.023902	35.159586	36	35	174.73326	11.486140099	402.01490349	0.1116797401	74.129702	0.9124100	76.642440	150.77214	136.29194	0.9039597	1.8385605	1.77828295
2.375	13.904774	1.410341	25.525736	26	25	347.61935	31.991197750	799.7799437	0.2221788683	102.10751	1.3014991	109.32593	211.43345	271.14309	1.2824039	2.6554664	2.48013524
	25.140650	1.679897	21.429875	22	21	527.95366	57.841970472	1214.6813799	0.3374384873	121.62318	1.6083429	135.10080	256.72398	411.80386	1.6040723	3.3858994	3.04812293
	38.072031	1.883443	19.113927	20	19	723.36860	87.593648469	1664.2793209	0.4623367953	136.35971	1.8745707	157.46394	293.82365	564.22751	1.9202930	4.1377874	3.58321724
	52.301876	2.040825	17.639918	18	17	889.13190	120.33274793	2045.6567149	0.5682834354	147.75406	2.1163724	177.77528	325.52935	693.52288	2.1304465	4.6937651	3.90112087
	67.536141	2.162149	16.650099	17	16	1080.5782	155.38275169	2486.1240270	0.6906452547	156.53778	2.3421736	196.74258	353.28036	842.85104	2.3857851	5.3843298	4.28402960
	83.536659	2.253245	15.976951	16	15	1253.0498	192.19569996	2882.9354994	0.8008794817	163.13310	2.5571321	214.79909	377.93220	977.37891	2.5861223	5.9912972	4.55020025
	100.09853	2.317682	15.532755	16	15	1501.4779	230.30017471	3454.5026207	0.9596608280	167.79827	2.7647891	232.24228	400.04056	1171.1528	2.9275851	6.9795281	5.04280613
	117.03732	2.357646	15.269463	16	15	1755.5599	269.27185675	4039.0778513	1.1220558271	170.69163	2.9678167	249.29660	419.98824	1369.3367	3.2604168	8.0222837	5.49280143

2-Inch

		134.18084	2.374373	15.161891	16	15	2012.7126	308.71452827	4630.7179241	1.2864134393	171.90267	3.1684159	266.14693	438.04960	1569.9158	3.5838767	9.1325854	5.89868074

3

Increment																	
*See attac																	
	rINNER (Height of Triangular Portion)	hINNER (Height of Arced Portion)	rINNER/RI	cos-1 (r/R)	theta (Central Angle [Radians]	theta (Central Angle [Degrees]	sin (theta) [Radians]	sin(theta) [Degrees]	AID (square inches [radians])	rOUTER	R2OUTER - r2OUTER	SQRT (R2OUTER - r2OUTER)	aOUTER (Chord Length)	rINNER	R2INNER - r2INNER	SQRT (R2INNER - r2INNER)	aINNER (Chord Length)
RINNER	1.421	0.1	0.9342537	0.3646355	0.7292711	41.784159	0.6663263	38.177686914	0.0728095548	1.6349441157	0.3894577	0.6240654	1.2481309	1.421	0.2942	0.5424020	1.0848041
1.521	1.321	0.2	0.8685075	0.5186129	1.0372258	59.428662	0.8609965	49.331469462	0.2038479955	1.5198882314	0.7524397	0.8674328	1.7348657	1.321	0.5684	0.7539230	1.5078461
ROUTER	1.221	0.3	0.8027613	0.6388846	1.2777692	73.210787	0.9573739	54.853483955	0.3706079241	1.4048323471	1.0889460	1.0435257	2.0870515	1.221	0.8226	0.9069729	1.8139459
1.75	1.121	0.4	0.7370151	0.7421529	1.4843059	85.044466	0.9962620	57.081610114	0.5645304027	1.2897764628	1.3989766	1.1827834	2.3655668	1.121	1.0568	1.0280077	2.0560155
DINNER	1.021	0.5	0.6712689	0.8348769	1.6697538	95.669850	0.9951076	57.015471129	0.7803770699	1.1747205785	1.6825315	1.2971243	2.5942486	1.021	1.271	1.1273863	2.2547727
3.042	0.921	0.6	0.6055226	0.9203738	1.8407476	105.46707	0.9637838	55.220748002	1.0144020311	1.0596646942	1.9396107	1.3926990	2.7853981	0.921	1.4652	1.2104544	2.4209089
DOUTER	0.821	0.7	0.5397764	1.0006247	2.0012495	114.66315	0.9087767	52.069070192	1.2636857466	0.9446088099	2.1702141	1.4731646	2.9463293	0.821	1.6394	1.2803905	2.5607811
3.5	0.721	0.8	0.4740302	1.0769339	2.1538679	123.40754	0.8347753	47.829105889	1.5258214374	0.8295529257	2.3743419	1.5408899	3.0817799	0.721	1.7936	1.3392535	2.6785070
	0.621	0.9	0.4082840	1.1502228	2.3004456	131.80582	0.7454081	42.708742863	1.7987437689	0.7144970414	2.5519939	1.5974961	3.1949923	0.621	1.9278	1.3884523	2.7769047
	0.521	1	0.3425378	1.2211795	2.4423590	139.93686	0.6436313	36.877357384	2.0806252858	0.5994411571	2.7031702	1.6441320	3.2882641	0.521	2.042	1.4289856	2.8579713
	0.421	1.1	0.2767915	1.2903426	2.5806853	147.86238	0.5319546	30.478756982	2.3698088351	0.4843852728	2.8278709	1.6816274	3.3632549	0.421	2.1362	1.4615744	2.9231489
	0.321	1.2	0.2110453	1.3581520	2.7163040	155.63275	0.4125836	23.639303055	2.6647606169	0.3693293885	2.9260958	1.7105834	3.4211669	0.321	2.2104	1.4867414	2.9734828
	0.221	1.3	0.1452991	1.4249810	2.8499620	163.29079	0.2875143	16.473361356	2.9640356917	0.2542735042	2.9978449	1.7314285	3.4628571	0.221	2.2646	1.5048587	3.0097175
	0.121	1.4	0.0795529	1.4911592	2.9823185	170.87426	0.1586015	9.0872016316	3.2662512392	0.1392176199	3.0431184	1.7444536	3.4889072	0.121	2.2988	1.5161794	3.0323588
	0.021	1.5	0.0138067	1.5569891	3.1139783	178.41781	0.0276107	1.5819811744	3.5700646547	0.0241617357	3.0619162	1.7498331	3.4996663	0.021	2.313	1.5208550	3.0417100

Horizontal Blinds L = 3' = 36"	VID (cubic inches [radians])	aOUTER (Chord Length)	Window Height/aO	Number of Blinds Required	Number of Blinds for Available Energy	VTOTAL (cubic inches [radians	Available Energy per Louver (KJ/louver)	Available Energy of All Louvers (KJ)	Available Energy of All Louvers (kWh)	Blackbody Surface Area	sINNER	Reflective Surface Area	Total Surface Area	Available PCM Mass	Mass/Total Surface Area	Mass/Black Surface Area	Mass/Reflec Surface Area
	2.6211439	1.2481309	67.300628	68	67	175.61664	6.0305571599	404.04732971	0.1122443481	39.052948	1.1092214	39.931971	78.984919	136.98098	1.7342675	3.5075708	3.43035869
	7.3385278	1.7348657	48.418733	49	48	352.24933	16.884006384	810.43230644	0.2251380947	54.282461	1.5776204	56.794337	111.07679	274.75448	2.4735542	5.0615700	4.83770910
	13.341885	2.0870515	40.248166	41	40	533.67541	30.696139736	1227.8455894	0.3410955047	65.302055	1.9434871	69.965535	135.26759	416.26682	3.0773581	6.3744826	5.94959812
	20.323094	2.3655668	35.509458	36	35	711.30830	46.758050755	1636.5317764	0.4546285274	74.016560	2.2576293	81.274656	155.29121	554.82047	3.5727743	7.4958965	6.82648812
	28.093574	2.5942486	32.379316	33	32	898.99438	64.635864548	2068.3476655	0.5745869814	81.171817	2.5396956	91.429043	172.60086	701.21561	4.0626426	8.6386585	7.66950625
	36.518473	2.7853981	30.157268	31	30	1095.5541	84.019321950	2520.5796585	0.7002170291	87.152721	2.7997772	100.79198	187.94470	854.53227	4.5467217	9.8049981	8.47817719
	45.492686	2.9463293	28.510050	29	28	1273.7952	104.66660785	2930.6650198	0.8141387425	92.188120	3.0439005	109.58042	201.76854	993.56028	4.9242576	10.777530	9.06695073
	54.929571	3.0817799	27.256975	28	27	1483.0984	126.37837726	3412.2161862	0.9479136565	96.426253	3.2760331	117.93719	214.36344	1156.8167	5.3965206	11.996906	9.80875277
	64.754775	3.1949923	26.291143	27	26	1683.6241	148.98356587	3873.5727127	1.0760784996	99.968571	3.4989779	125.96320	225.93177	1313.2268	5.8124929	13.136397	10.4254798
	74.902510	3.2882641	25.545392	26	25	1872.5627	172.33081203	4308.2703008	1.1968374895	102.88696	3.7148281	133.73381	236.62078	1460.5989	6.1727416	14.196151	10.9216877
	85.313118	3.3632549	24.975805	25	24	2047.5148	196.28285963	4710.7886311	1.3086570817	105.23336	3.9252224	141.30800	246.54137	1597.0615	6.4778643	15.176380	11.3019890
	95.931382	3.4211669	24.553025	25	24	2302.3531	220.71266946	5297.1040670	1.4715355098	107.04538	4.1314984	148.73394	255.77932	1795.8354	7.0210344	16.776393	12.0741466
	106.70528	3.4628571	24.257425	25	24	2560.9268	245.50056231	5892.0134956	1.6368013490	108.34983	4.3347922	156.05252	264.40235	1997.5229	7.5548606	18.435865	12.8003247
	117.58504	3.4889072	24.076306	25	24	2822.0410	270.53200410	6492.7680984	1.8036909777	109.16491	4.5361064	163.29983	272.46474	2201.1920	8.0788140	20.163914	13.4794507
	128.52232	3.4996663	24.002287	25	24	3084.5358	295.69579161	7096.6989987	1.9714629818	109.50156	4.7363610	170.50899	280.01056	2405.9379	8.5923115	21.971722	14.1103283

3-Inch

	Vertical Blinds L = 7' = 84"	VID (cubic inches [radians	aOUTER (Chord Length)	Window Height/aC	Number of Blinds Required	Number of Blinds for Available Energy	VTOTAL (cubic inches [radians	Available Energy per Louver (KJ/louver)	Available Energy of All Louvers (KJ)	Available Energy of All Louvers (kWh)	Blackbody Surface Area	sINNER	Reflective Surface Area	Total Surface Area	Available PCM Mass	Mass/Total Surface Area	Mass/Black Surface Area	Mass/Reflect Surface Area
		6.1160026	1.248130	28.843126	29	28	171.24807	14.071300039	393.99640111	0.1094522002	91.123546	1.1092214	93.174599	184.29814	133.57349	0.7247685	1.4658505	1.43358273
		17.123231	1.734865	20.750885	21	20	342.46463	39.396014896	787.92029793	0.2188842587	126.65907	1.5776204	132.52012	259.17919	267.12241	1.0306475	2.1089875	2.01571212
		31.131065	2.087051	17.249214	18	17	529.22811	71.624326052	1217.6135428	0.3382530422	152.37146	1.9434871	163.25291	315.62437	412.79793	1.3078772	2.7091551	2.52857920
		47.420553	2.365566	15.218339	16	15	711.30830	109.10211843	1636.5317764	0.4546285274	172.70530	2.2576293	189.64086	362.34617	554.82047	1.5311890	3.2125270	2.92563776
		65.551673	2.594248	13.876850	14	13	852.17176	150.81701727	1960.6212246	0.5446605762	189.40090	2.5396956	213.33443	402.73534	664.69397	1.6504485	3.5094550	3.11573691
		85.209770	2.785398	12.924543	13	12	1022.5172	196.04508455	2352.5410146	0.6535358938	203.35634	2.7997772	235.18128	438.53763	797.56345	1.8186887	3.9219992	3.39127087
		106.14960	2.946329	12.218593	13	12	1273.7952	244.22208498	2930.6650198	0.8141387425	215.10561	3.0439005	255.68764	470.79326	993.56028	2.1103961	4.6189416	3.88583602
		128.16900	3.081779	11.681560	12	11	1409.8590	294.88288029	3243.7116832	0.9011031056	224.99459	3.2760331	275.18678	500.18137	1099.6900	2.1985825	4.8876287	3.99615853
		151.09447	3.194992	11.267632	12	11	1662.0392	347.62832037	3823.9115241	1.0622826214	233.25999	3.4989779	293.91414	527.17414	1296.3906	2.4591316	5.5577064	4.41077993
		174.77252	3.288264	10.948025	11	10	1747.7252	402.10522808	4021.0522808	1.1170483236	240.06958	3.7148281	312.04556	552.11515	1363.2256	2.4690966	5.6784605	4.36867509
		199.06394	3.363254	10.703916	11	10	1990.6394	457.99333913	4579.9333913	1.2723054961	245.54451	3.9252224	329.71868	575.26320	1552.6987	2.6991101	6.3234918	4.70916209
		223.83989	3.421166	10.522725	11	10	2238.3989	514.99622874	5149.9622874	1.4306595234	249.77255	4.1314984	347.04587	596.81842	1745.9511	2.9254310	6.9901641	5.03089443
		248.97899	3.462857	10.396039	11	10	2489.7899	572.83464540	5728.3464540	1.5913346449	252.81627	4.3347922	364.12254	616.93882	1942.0361	3.1478586	7.6816105	5.33346864
		274.36510	3.488907	10.318417	11	10	2743.6510	631.24134290	6312.4134290	1.7535884505	254.71814	4.5361064	381.03294	635.75108	2140.0478	3.3661725	8.4016309	5.61643779
		299.88543	3.499666	10.286694	11	10	2998.8543	689.95684710	6899.5684710	1.9167001212	255.50364	4.7363610	397.85433	653.35797	2339.1063	3.5801298	9.1548845	5.87930349

Increment
*See atta

	rINNER (Height of Triangular Portion)	hINNER (Height of Arced Portion)	rINNER/RI	cos-1 (r/R)	theta (Central Angle [Radians]	theta (Central Angle [Degrees]	sin (theta) [Radians]	sin(theta) [Degrees]	AID (square inches [radians])	rOUTER	R2OUTER - r2OUTER	SQRT (R2OUTER - r2OUTER)	aOUTER (Chord Length)	rINNER	R2INNER - r2INNER	SQRT (R2INNER - r2INNER)	aINNER (Chord Length)
RINNER	1.899	0.1	0.9499749	0.3176405	0.6352810	36.398922	0.5934037	33.999530661	0.08367085265	2.1374437218	0.4938343	0.7027334	1.4054669	1.899	0.3898000	0.6243396	1.2486793
1.999	1.799	0.2	0.8999499	0.4511415	0.9022831	51.697015	0.7847440	44.962523852	0.2348430720	2.0248874437	0.9623308	0.9809846	1.9619692	1.799	0.7596000	0.8715503	1.7431006
ROUTER	1.699	0.3	0.8499249	0.5549534	1.1099069	63.592982	0.8956572	51.317382840	0.4280708658	1.9123311655	1.4054895	1.1855334	2.3710668	1.699	1.1094	1.0532805	2.1065611
2.25	1.599	0.4	0.7998999	0.6436678	1.2873356	73.758901	0.9600933	55.009294960	0.6538304075	1.7997748874	1.8233103	1.3503000	2.7006001	1.599	1.4392	1.1996666	2.3993332
DINNER	1.499	0.5	0.7498749	0.7229233	1.4458466	82.840908	0.9922039	56.849097883	0.9063782890	1.6872186093	2.2157933	1.4885541	2.9771082	1.499	1.749	1.3224976	2.6449952
3.998	1.399	0.6	0.6998499	0.7956089	1.5912179	91.170070	0.9997914	57.283832580	1.1816702920	1.5746623311	2.5829385	1.6071523	3.2143046	1.399	2.0388	1.4278655	2.8557310
DOUTER	1.299	0.7000000000	0.6498249	0.8634422	1.7268845	98.943195	0.9878429	56.599231781	1.4766054516	1.4621060530	2.9247458	1.7101888	3.4203776	1.299	2.3086	1.5194077	3.0388155
4.5	1.199	0.8000000000	0.5997998	0.9275453	1.8550906	106.28886	0.9598598	54.995916782	1.7886716184	1.3495497748	3.2412154	1.8003375	3.6006751	1.199	2.5584	1.5994999	3.1989998
	1.099	0.9000000000	0.5497748	0.9887016	1.9774032	113.29685	0.9184680	52.624343830	2.1157529570	1.2369934967	3.5323470	1.8794539	3.7589078	1.099	2.7882	1.6697904	3.3395808
	0.9989999	1	0.4997498	1.0474863	2.0949726	120.03309	0.8657364	49.603045550	2.4560146010	1.1244372186	3.7981409	1.9488819	3.8977639	0.9989999	2.998	1.7314733	3.4629467
	0.8989999	1.1	0.4497248	1.1043390	2.2086781	126.54793	0.8033589	46.029076835	2.8078284145	1.0118809404	4.0385969	2.0096260	4.0192521	0.8989999	3.1878	1.7854411	3.5708822
	0.7989999	1.2	0.3996998	1.1596069	2.3192138	132.88116	0.7327665	41.984433467	3.1697224930	0.8993246623	4.2537151	2.0624536	4.1249073	0.7989999	3.3576	1.8323755	3.6647510
	0.6989999	1.3	0.3496748	1.2135723	2.4271446	139.06514	0.6552005	37.540224406	3.5403452362	0.7867683841	4.4434955	2.1079600	4.2159200	0.6989999	3.5074	1.8728053	3.7456107
	0.5989999	1.4	0.2996498	1.2664707	2.5329414	145.12685	0.5717613	32.759514243	3.9184387899	0.6742121060	4.6079380	2.1466108	4.2932216	0.5989999	3.6372	1.9071444	3.8142889
	0.4989999	1.5	0.2496248	1.3185035	2.6370070	151.08937	0.4834446	27.699340693	4.3028187379	0.5616558279	4.7470427	2.1787709	4.3575418	0.4989999	3.747	1.9357169	3.8714338
	0.3989999	1.6	0.1995997	1.3698468	2.7396936	156.97288	0.3911667	22.412201388	4.6923580726	0.4490995497	4.8608095	2.2047243	4.4094487	0.3989999	3.8368	1.9587751	3.9175502
	0.299	1.7	0.1495747	1.4206581	2.8413162	162.79542	0.2957842	16.947190099	5.0859741505	0.3365432716	4.9492386	2.2246884	4.4493768	0.299	3.9066	1.9765120	3.9530241
	0.1989999	1.8	0.0995497	1.4710813	2.9421627	168.57350	0.1981105	11.350897784	5.4826177432	0.2239869934	5.0123298	2.2388233	4.4776466	0.1989999	3.9564	1.9890701	3.9781402
	0.099	1.9	0.0495247	1.5212512	3.0425025	174.32255	0.0989279	5.6681557698	5.8812635496	0.1114307153	5.0500831	2.2472390	4.4944780	0.099	3.9862	1.9965470	3.9930940

	Horizontal Blinds L = 3' = 36"	VID (cubic inches [radians])	aOUTER (Chord Length)	Window Height/aO	Number of Blinds Required	Number of Blinds for Available Energy	VTOTAL (cubic inches [radians	Available Energy per Louver (KJ/louver)	Available Energy of All Louvers (KJ)	Available Energy of All Louvers (kWh)	Blackbody Surface Area	sINNER	Reflective Surface Area	Total Surface Area	Available PCM Mass	Mass/Total Surface Area	Mass/Black Surface Area	Mass/Reflec Surface Area
-0.1		3.0121506956	1.4054669	59.766613	60	59	177.71689	6.9301599282	408.87943576	0.1135867072	44.952454	1.2699268	45.717365	90.669820	138.61917	1.5288347	3.0836842	3.03209019
-0.2		8.4543505932	1.9619692	42.814126	43	42	355.08272	19.451218621	816.95118209	0.2269490383	62.751624	1.8036639	64.931902	127.68352	276.96452	2.1691484	4.4136630	4.26546139
-0.3		15.410551171	2.3710668	35.427090	36	35	539.36929	35.455591366	1240.9456978	0.3447347148	75.836202	2.2187039	79.873341	155.70954	420.70804	2.7018770	5.5475885	5.26718974
-0.4		23.537894672	2.7006001	31.104196	32	31	729.67473	54.154453391	1678.7880551	0.4663673217	86.375996	2.5733840	92.641824	179.01782	569.14629	3.1792716	6.5891719	6.14351340
-0.5		32.629618406	2.9771082	28.215299	29	28	913.62931	75.072098578	2102.0187602	0.5839408115	95.219829	2.8902473	104.04890	199.26873	712.63086	3.5762301	7.4840594	6.84899916
-0.6		42.540130512	3.2143046	26.133179	27	26	1106.0433	97.873558666	2544.7125253	0.7069211395	102.80631	3.1808446	114.51040	217.31672	862.71384	3.9698456	8.3916422	7.53393406
-0.7		53.157796259	3.4203776	24.558691	25	24	1275.7871	122.30199174	2935.2478018	0.8154118393	109.39736	3.4520421	124.27351	233.67087	995.11394	4.2586134	9.0963250	8.00744968
-0.8		64.392178262	3.6006751	23.328958	24	23	1481.0201	148.14932537	3407.4344836	0.9465852995	115.16399	3.7083261	133.49974	248.66373	1155.1956	4.6456137	10.030875	8.65316781
-0.9		76.167106452	3.7589078	22.346916	23	22	1675.6763	175.24031242	3855.2868734	1.0709986934	120.22490	3.9528290	142.30184	262.52675	1307.0275	4.9786451	10.871520	9.18489529
-1		88.416525639	3.8977639	21.550817	22	21	1856.7470	203.42297743	4271.8825261	1.1867289657	124.66608	4.1878504	150.76261	275.42869	1448.2626	5.2582127	11.617134	9.60624549
-1.1		101.08182292	4.0192521	20.899410	21	20	2021.6364	232.56246764	4651.2493529	1.2921170702	128.55176	4.4151475	158.94531	287.49707	1576.8764	5.4848434	12.266470	9.92087415
-1.2		114.11000975	4.1249073	20.364093	21	20	2282.2001	262.53687046	5250.7374092	1.4586548522	131.93103	4.6361085	166.89990	298.83094	1780.1161	5.9569337	13.492777	10.6657706
-1.3		127.45242850	4.2159200	19.924476	20	19	2421.5961	293.23423760	5571.4505144	1.5477489529	134.84198	4.8518621	174.66703	309.50902	1888.8449	6.1027137	14.007840	10.8139751
-1.4		141.06379643	4.2932216	19.565726	20	19	2680.2121	324.55038548	6166.4573242	1.7130418446	137.31440	5.0633499	182.28059	319.59500	2090.5654	6.5412958	15.224662	11.4689410
-1.5		154.90147456	4.3575418	19.276923	20	19	2943.1280	356.38721310	6771.3570490	1.8810829882	139.37161	5.2713771	189.76957	329.14119	2295.6398	6.9746354	16.471358	12.0969855
-1.6		168.92489061	4.4094487	19.050000	20	19	3209.5729	388.65137442	7384.3761140	2.0513796844	141.03180	5.4766476	197.15931	338.19112	2503.4668	7.4025209	17.751079	12.6976849

-1.7		183.0950694	4.4493768	18.879048	19	18	3295.7112	421.25319791	7582.5575625	2.1064344908	142.30886	5.6797911	204.47248	346.78135	2570.6547	7.4128979	18.063911	12.5721307
-1.8		197.3742387	4.4776466	18.759854	19	18	3552.7362	454.10577973	8173.9040351	2.2707105409	143.21304	5.8813833	211.72980	354.94285	2771.1343	7.8072689	19.349733	13.0880692
		211.7254877	4.4944780	18.689600	19	18	3811.0587	487.12419779	8768.2355603	2.4358158386	143.75138	6.0819626	218.95065	362.70204	2972.6258	8.1957791	20.678937	13.5766930
	Vertical Blinds L = 7' = 84"	VID (cubic inches [radians])	aOUTER (Chord Length)	Window Height/aC	Number of Blinds Required	Number of Blinds for Available Energy	VTOTAL (cubic inches [radians	Available Energy per Louver (KJ/louver)	Available Energy of All Louvers (KJ)	Available Energy of All Louvers (kWh)	Blackbody Surface Area	sINNER	Reflective Surface Area	Total Surface Area (All Louvers)	Available PCM Mass [g]	Total Surface Area/Mass [g/in^3]	Mass/Black Surface Area	Mass/Reflect Surface Area
		7.0283516231	1.405466	25.614262	26	25	175.70879	16.170373165	404.25932914	0.1123032416	104.88906	1.2699268	106.67385	5289.0728	137.05285	38.591481	1.3066458	1.28478398
		19.726818050	1.961969	18.348911	19	18	355.08272	45.386176782	816.95118209	0.2269490383	146.42045	1.8036639	151.50777	5362.7081	276.96452	19.362436	1.8915698	1.82805488
		35.957952732	2.371066	15.183038	16	15	539.36929	82.729713189	1240.9456978	0.3447347148	176.95113	2.2187039	186.37113	5449.8340	420.70804	12.953957	2.3775379	2.25736703
		54.921754235	2.700600	13.330370	14	13	713.98280	126.36039124	1642.6850862	0.4563379169	201.54399	2.5733840	216.16425	5430.2072	556.90658	9.7506608	2.7632011	2.57631207
		76.135776281	2.977108	12.092271	13	12	913.62931	175.16823001	2102.0187602	0.5839408115	222.17960	2.8902473	242.78077	5579.5245	712.63086	7.8294736	3.2074540	2.93528535
		99.260304529	3.214304	11.199934	12	11	1091.8633	228.37163688	2512.0880057	0.6978580480	239.88141	3.1808446	267.19094	5577.7959	851.65341	6.5493730	3.5503101	3.18743364
		124.03485793	3.420377	10.525153	11	10	1240.3485	285.37131407	2853.7131407	0.7927615104	255.26050	3.4520421	289.97154	5452.3204	967.47189	5.6356371	3.7901354	3.33643736
		150.24841594	3.600675	9.9981249	10	9	1352.2357	345.68175921	3111.1358329	0.8642735343	268.71598	3.7083261	311.49939	5221.9384	1054.7438	4.9509066	3.9251251	3.38602219
		177.72324838	3.758907	9.5772499	10	9	1599.5092	408.89406233	3680.0465610	1.0223169346	280.52478	3.9528290	332.03763	5513.0618	1247.6172	4.4188728	4.4474401	3.75745716
		206.30522649	3.897763	9.2360647	10	9	1856.7470	474.65361401	4271.8825261	1.1867289657	290.88752	4.1878504	351.77943	5784.0026	1448.2626	3.9937524	4.9787720	4.11696235
		235.85758682	4.019252	8.9568901	9	8	1886.8606	542.64575784	4341.1660627	1.2059759322	299.95410	4.4151475	370.87239	5366.6120	1471.7513	3.6464121	4.9065883	3.96834966
		266.25668941	4.124907	8.7274687	9	8	2130.0535	612.58603107	4900.6882486	1.3614111954	307.83908	4.6361085	389.43312	5578.1776	1661.4417	3.3574319	5.3971110	4.26630826
		297.38899984	4.215920	8.5390613	9	8	2379.1119	684.21322107	5473.7057686	1.5205954625	314.63130	4.8518621	407.55641	5777.5017	1855.7073	3.1133690	5.8980379	4.55325268
		329.14885835	4.293221	8.3853112	9	8	2633.1908	757.28423280	6058.2738624	1.6829884789	320.40026	5.0633499	425.32139	5965.7733	2053.8888	2.9046232	6.4103843	4.82902782
		361.43677398	4.357541	8.2615385	9	8	2891.4941	831.57016391	6652.5613113	1.8480815322	325.20044	5.2713771	442.79568	6143.9690	2255.3654	2.7241567	6.9353087	5.09346761
		394.15807810	4.409448	8.1642858	9	8	3153.2646	906.85320699	7254.8256559	2.0153905672	329.07422	5.4766476	460.03840	6312.9010	2459.5464	2.5666931	7.4741388	5.34639365
		427.22182864	4.449376	8.0910206	9	8	3417.7746	982.92412847	7863.3930278	2.1844505831	332.05402	5.6797911	477.10245	6473.2518	2665.8642	2.4282001	8.0284049	5.58761366
		460.53989043	4.477646	8.0399377	9	8	3684.3191	1059.5801527	8476.6412216	2.3548109313	334.16378	5.8813833	494.03620	6625.5999	2873.7689	2.3055437	8.5998814	5.81691966
		494.02613817	4.494478	8.0098288	9	8	3952.2091	1136.6231281	9092.9850255	2.5260312401	335.41989	6.0819626	510.88486	6770.4381	3082.7231	2.1962524	9.1906386	6.03408577

Increment
*See attac

	rINNER (Height of Triangular Portion)	hINNER (Height of Arced Portion)	rINNER/RI	cos-1 (r/R)	theta (Central Angle [Radians]	theta (Central Angle [Degrees]	sin (theta) [Radians]	sin(theta) [Degrees]	AID (square inches [radians])	rOUTER	R2OUTER - r2OUTER	SQRT (R2OUTER - r2OUTER)	aOUTER (Chord Length)	rINNER	R2INNER - r2INNER	SQRT (R2INNER - r2INNER)	aINNER (Chord Length)
RINNER	1.958	0.1	0.9514091	0.3130161	0.6260323	35.869009	0.5859341	33.571552601	0.0849152024	2.6463445092	0.7336029	0.8565062	1.7130125	1.958	0.4016000	0.6337191	1.2674383
2.058	1.858	0.2	0.9028182	0.4445174	0.8890349	50.937949	0.7764639	44.488107990	0.2383895229	2.5111890184	1.4306719	1.1961070	2.3922140	1.858	0.7832000	0.8849858	1.7699717
ROUTER	1.758	0.3	0.8542274	0.5467333	1.0934667	62.651027	0.8882248	50.891537108	0.4346369106	2.3760335276	2.0912069	1.4461005	2.8922011	1.758	1.1448	1.0699532	2.1399065
2.7815	1.658	0.4	0.8056365	0.6340471	1.2680942	72.656451	0.9545344	54.690798188	0.6640199450	2.2408780369	2.7152078	1.6477887	3.2955775	1.658	1.4864	1.2191800	2.4383601
DINNER	1.558	0.5	0.7570456	0.7120168	1.4240337	81.591122	0.9892496	56.679831909	0.9207343324	2.1057225461	3.3026748	1.8173262	3.6346525	1.558	1.808	1.3446189	2.6892378
5.016	1.458	0.6	0.7084548	0.7834899	1.5669798	89.781333	0.9999927	57.295362249	1.2006985095	1.9705670553	3.8536077	1.9630608	3.9261216	1.458	2.1096	1.4524462	2.9048924
DOUTER	1.358	0.7000000	0.6598639	0.8501586	1.7003173	97.421005	0.9916238	56.815863056	1.5007873116	1.8354115646	4.3680066	2.0899776	4.1799553	1.358	2.3912	1.5463505	3.0927010
5.563	1.258	0.8000000	0.6112730	0.9131281	1.8262562	104.63677	0.9675471	55.436369749	1.8184727657	1.7002560738	4.8458715	2.2013340	4.4026680	1.258	2.6528	1.6287418	3.2574836
	1.158	0.9000000	0.5626822	0.9731695	1.9463390	111.51701	0.9303087	53.302762961	2.1516290740	1.5651005830	5.2872024	2.2993917	4.5987834	1.158	2.8944	1.7012936	3.4025872
	1.058	1	0.5140913	1.0308483	2.0616967	118.12652	0.8819087	50.529648762	2.4984158207	1.4299450923	5.6919992	2.3857911	4.7715822	1.058	3.116	1.7652195	3.5304390
	0.9579999	1.1	0.4655004	1.0865963	2.1731926	124.51476	0.8239801	47.210587776	2.8572028559	1.2947896015	6.0602621	2.4617599	4.9235199	0.9579999	3.3176	1.8214280	3.6428560
	0.8579999	1.2	0.4169096	1.1407536	2.2815072	130.72073	0.7578982	43.424373148	3.2265192550	1.1596341107	6.3919909	2.5282387	5.0564774	0.8579999	3.4992	1.8706148	3.7412297
	0.7579999	1.3	0.3683187	1.1935963	2.3871926	136.77606	0.6848515	39.239105107	3.6050170580	1.0244786200	6.6871858	2.5859593	5.1719187	0.7579999	3.6608	1.9133217	3.8266434
	0.6579999	1.4	0.3197278	1.2453540	2.4907080	142.70706	0.6058903	34.714960982	3.9914445261	0.8893231292	6.9458466	2.6354974	5.2709948	0.6579999	3.8024	1.9499743	3.8999487
	0.5579999	1.5	0.2711370	1.2962222	2.5924444	148.53612	0.5219608	29.906155387	4.3846257515	0.7541676384	7.1679734	2.6773071	5.3546142	0.5579999	3.924	1.9809088	3.9618177
	0.4579999	1.6	0.2225461	1.3463709	2.6927419	154.28274	0.4339303	24.862378566	4.7834446345	0.6190121477	7.3535662	2.7117459	5.4234919	0.4579999	4.0256	2.0063897	4.0127795
	0.3579999	1.7	0.1739552	1.3959515	2.7919030	159.96426	0.3426061	19.629888805	5.1868319185	0.4838566569	7.5026249	2.7390920	5.4781840	0.3579999	4.1072	2.0266228	4.0532456
	0.2579999	1.8	0.1253644	1.4451011	2.8902023	165.59639	0.2487508	14.252371145	5.5937543943	0.3487011661	7.6151497	2.7595560	5.5191121	0.2579999	4.1688	2.0417639	4.0835278
	0.1579999	1.9	0.0767735	1.4939471	2.9878942	171.19373	0.1530939	8.7716370378	6.0032056383	0.2135456754	7.6911404	2.7732905	5.5465811	0.1579999	4.2104	2.0519259	4.1038518
	0.0579999	2	0.0281827	1.5426098	3.0852197	176.77007	0.0563430	3.2282169263	6.4141978198	0.0783901846	7.7305972	2.7803951	5.5607903	0.0579999	4.232	2.0571825	4.1143650

Horizontal Blinds L = 3' = 36"	VID (cubic inches [radians])	aOUTER (Chord Length)	Window Height/aC	Number of Blinds Required	Number of Blinds for Available Energy	VTOTAL (cubic inches [radians	Available Energy per Louver (KJ/louver)	Available Energy of All Louvers (KJ)	Available Energy of All Louvers (kWh)	Blackbody Surface Area	sINNER	Reflective Surface Area	Total Surface Area	Available PCM Mass	Mass/Total Surface Area	Mass/Black Surface Area	Mass/Reflec Surface Area
	3.0569472	1.7130125	49.036418	50	49	149.79041	7.0332250084	344.62802541	0.0957376654	45.627781	1.2883744	46.381481	92.009262	116.83652	1.2698343	2.5606444	2.51903390
	8.5820228	2.3922140	35.113915	36	35	300.37079	19.744958570	691.07354997	0.1919802321	63.718983	1.8296338	65.866820	129.58580	234.28922	1.8079852	3.6769140	3.55701432
	15.646928	2.8922011	29.043622	30	29	453.76093	35.999433567	1043.9835734	0.2900186367	77.036635	2.2503544	81.012761	158.04939	353.93352	2.2393855	4.5943534	4.36886144
	23.904718	3.2955775	25.488703	26	25	597.61795	54.998416639	1374.9604159	0.3819640035	87.780963	2.6097380	93.950570	181.73153	466.14200	2.5650033	5.3102857	4.96156648
	33.146435	3.6346525	23.110874	24	23	762.36802	76.261158730	1754.0066507	0.4872630475	96.812561	2.9306614	105.50381	202.31637	594.64706	2.9391939	6.1422511	5.63626145
	43.225146	3.9261216	21.395159	22	21	907.72807	99.449598430	2088.4415670	0.5801690673	104.57612	3.2248445	116.09440	220.67053	708.02789	3.2085294	6.7704543	6.09872538
	54.028343	4.1799553	20.095908	21	20	1080.5668	124.30488942	2486.0977885	0.6906379656	111.33723	3.4992530	125.97310	237.31034	842.84215	3.5516451	7.5701729	6.69065140
	65.465019	4.4026680	19.079339	20	19	1243.8353	150.61764869	2861.7353252	0.7949900733	117.26941	3.7584353	135.30367	252.57308	970.19158	3.8412310	8.2731853	7.17047485
	77.458646	4.5987834	18.265700	19	18	1394.2556	178.21180394	3207.8124710	0.8911303044	122.49314	4.0055656	144.20036	266.69350	1087.5193	4.0777873	8.8782064	7.54172432
	89.942969	4.7715822	17.604223	18	17	1529.0304	206.93492004	3517.8936408	0.9772708534	127.09580	4.2429719	152.74698	279.84279	1192.6437	4.2618348	9.3838169	7.80796916
	102.85930	4.9235199	17.060964	18	17	1748.6081	236.65197749	4023.0836173	1.1176126289	131.14281	4.4724304	161.00749	292.15031	1363.9143	4.6685363	10.400221	8.47112339
	116.15469	5.0564774	16.612355	17	16	1858.4750	267.24114478	4275.8583165	1.1878334403	134.68427	4.6953419	169.03230	303.71657	1449.6105	4.7729056	10.763027	8.57593784
	129.78061	5.1719187	16.241554	17	16	2076.4898	298.59077520	4777.4524032	1.3271762776	137.75916	4.9128424	176.86232	314.62149	1619.6620	5.1479701	11.757200	9.15775602

5-Inch

		143.69200	5.2709948	15.936270	16	15	2155.3800	330.59719164	4958.9578747	1.3775984975	140.39815	5.1258772	184.53157	324.92973	1681.1964	5.1740307	11.974491	9.11061638
		157.84652	5.3546142	15.687404	16	15	2367.6979	363.16299785	5447.4449678	1.5133002120	142.62543	5.3352506	192.06902	334.69446	1846.8043	5.5178814	12.948632	9.61531608
		172.20400	5.4234919	15.488176	16	15	2583.0601	396.19575124	5942.9362686	1.6509476954	144.46006	5.5416629	199.49986	343.95993	2014.7868	5.8576209	13.947016	10.0991891
		186.72594	5.4781840	15.333548	16	15	2800.8892	429.60688908	6444.1033363	1.7901719068	145.91684	5.7457365	206.84651	352.76335	2184.6936	6.1930854	14.972182	10.5619067
		201.37515	5.5191121	15.219839	16	15	3020.6273	463.31083431	6949.6625147	1.9306162466	147.00700	5.9480364	214.12931	361.13631	2356.0893	6.5240997	16.027055	11.0031145
		216.11540	5.5465811	15.144464	16	15	3241.7310	497.22422844	7458.3634267	2.0719333599	147.73866	6.1490864	221.36711	369.10577	2528.5502	6.8504758	17.115019	11.4224294
		230.91112	5.5607903	15.105766	16	15	3463.6668	531.26525297	7968.9787945	2.2137823091	148.11714	6.3493823	228.57776	376.69490	2701.6601	7.1720112	18.240023	11.8194354

	Vertical Blinds L = 7' = 84"	VID (cubic inches [radians	aOUTER (Chord Length)	Window Height/aC	Number of Blinds Required	Number of Blinds for Available Energy	VTOTAL (cubic inches [radians	Available Energy per Louver (KJ/louver)	Available Energy of All Louvers (KJ)	Available Energy of All Louvers (kWh)	Blackbody Surface Area	sINNER	Reflective Surface Area	Total Surface Area	Available PCM Mass	Mass/Total Surface Area	Mass/Black Surface Area	Mass/Reflect Surface Area
		7.1328770	1.713012	21.015608	22	21	149.79041	16.410858353	344.62802541	0.0957376654	106.46482	1.2883744	108.22345	214.68828	116.83652	0.5442147	1.0974190	1.07958595
		20.024719	2.392214	15.048820	16	15	300.37079	46.071569998	691.07354997	0.1919802321	148.67762	1.8296338	153.68924	302.36687	234.28922	0.7748508	1.5758203	1.52443470
		36.509500	2.892201	12.447266	13	12	438.11400	83.998678323	1007.9841398	0.2800179940	179.75214	2.2503544	189.02977	368.78192	341.72892	0.9266422	1.9011117	1.80780473
		55.777675	3.295577	10.923730	11	10	557.77675	128.32963882	1283.2963882	0.3564997366	204.82224	2.6097380	219.21799	424.04024	435.06586	1.0260013	2.1241143	1.98462659
		77.341683	3.634652	9.9046605	10	9	696.07515	177.94270370	1601.4843333	0.4448923478	225.89597	2.9306614	246.17555	472.07153	542.93862	1.1501193	2.4034895	2.20549361
		100.85867	3.926121	9.1693542	10	9	907.72807	232.04906300	2088.4415670	0.5801690673	244.01096	3.2248445	270.88694	514.89790	708.02789	1.3750840	2.9016232	2.61373945
		126.06613	4.179955	8.6125322	9	8	1008.5290	290.04474199	2320.3579359	0.6445954346	259.78689	3.4992530	293.93725	553.72414	786.65267	1.4206580	3.0280691	2.67626056
		152.75171	4.402668	8.1768599	9	8	1222.0136	351.44118029	2811.5294423	0.7810428790	273.62863	3.7584353	315.70857	589.33720	953.17068	1.6173604	3.4834464	3.01914730
		180.73684	4.598783	7.8281571	8	7	1265.1578	415.82754254	2910.7927978	0.8086182392	285.81732	4.0055656	336.46751	622.28484	986.82315	1.5858061	3.4526358	2.93289279
		209.86692	4.771582	7.5446671	8	7	1469.0685	482.84814678	3379.9370274	0.9389465062	296.55688	4.2429719	356.40963	652.96652	1145.8734	1.7548731	3.8639246	3.21504612
		240.00503	4.923519	7.3118420	8	7	1680.0352	552.18794747	3865.3156323	1.0737846826	305.99990	4.4724304	375.68415	681.68406	1310.4275	1.9223385	4.2824441	3.48810963
		271.02761	5.056477	7.1195808	8	7	1897.1933	623.56267116	4364.9386981	1.2125799703	314.26329	4.6953419	394.40871	708.67201	1479.8107	2.0881462	4.7088247	3.75197280
		302.82143	5.171918	6.9606662	7	6	1816.9285	696.71180881	4180.2708528	1.1612792429	321.43804	4.9128424	412.67876	734.11681	1417.2043	1.9304888	4.4089500	3.43415850
		335.28134	5.270994	6.8298302	7	6	2011.6880	771.39344717	4628.3606830	1.2857585977	327.59569	5.1258772	430.57368	758.16937	1569.1166	2.0696123	4.7897964	3.64424655
		368.30856	5.354614	6.7231733	7	6	2209.8513	847.38032833	5084.2819700	1.4124135312	332.79269	5.3352506	448.16105	780.95374	1723.6840	2.2071525	5.1794529	3.84612643
		401.80934	5.423491	6.6377898	7	6	2410.8560	924.45675289	5546.7405173	1.5408845157	337.07348	5.5416629	465.49968	802.57317	1880.4677	2.3430483	5.5788065	4.03967566
		435.69388	5.478184	6.5715207	7	6	2614.1632	1002.4160745	6014.4964472	1.6708271130	340.47263	5.7457365	482.64186	823.11449	2039.0473	2.4772341	5.9888730	4.22476270
		469.87536	5.519112	6.5227882	7	6	2819.2522	1081.0586134	6486.3516804	1.8019084968	343.01634	5.9480364	499.63506	842.65140	2199.0167	2.6096399	6.4108220	4.40124583
		504.26927	5.546581	6.4904847	7	6	3025.6156	1160.1898663	6961.1391982	1.9338044692	344.72355	6.1490864	516.52325	861.24681	2359.9802	2.7401903	6.8460079	4.56897178
		538.79261	5.560790	6.4738999	7	6	3232.7557	1239.6189236	7437.7135416	2.0661968218	345.60666	6.3493823	533.34811	878.95478	2521.5494	2.8688045	7.2960092	4.72777418

6-Inch

Increment																	
*See attac																	
	rINNER (Height of Triangular Portion)	hINNER (Height of Arced Portion)	rINNER/RI	cos-1 (r/R)	theta (Central Angle [Radians]	theta (Central Angle [Degrees]	sin (theta) [Radians]	sin(theta) [Degrees]	AID (square inches [radians])	rOUTER	R2OUTER - r2OUTER	SQRT (R2OUTER - r2OUTER)	aOUTER (Chord Length)	rINNER	R2INNER - r2INNER	SQRT (R2INNER - r2INNER)	aINNER (Chord Length)
RINNER	2.9155	0.1	0.9668380	0.2582515	0.5165030	29.593443	0.4938423	28.295082870	0.1030294138	3.2026508870	0.7156835	0.8459808	1.6919616	2.9155	0.5931	0.7701298	1.5402597
3.0155	2.8155	0.2	0.9336760	0.3662523	0.7325046	41.969426	0.6687339	38.315633696	0.2899412148	3.0928017741	1.4072334	1.1862687	2.3725374	2.8155	1.1662	1.0799074	2.1598148
ROUTER	2.7155	0.3	0.9005140	0.4498461	0.8996923	51.548571	0.7831356	44.870364880	0.5299390251	2.9829526612	2.0746496	1.4403644	2.8807288	2.7155	1.7193	1.3112208	2.6224416
3.3125	2.6155	0.4	0.8673520	0.5209394	1.0418788	59.695261	0.8633538	49.466529977	0.8116855158	2.8731035483	2.7179322	1.6486152	3.2972305	2.6155	2.2524	1.5007997	3.0015995
DINNER	2.5155	0.5	0.8341900	0.5841339	1.1682678	66.936817	0.9200734	52.716323633	1.1284458205	2.7632544354	3.3370811	1.8267679	3.6535359	2.5155	2.7655	1.6629792	3.3259585
6.031	2.4155	0.6	0.8010280	0.6417857	1.2835715	73.543232	0.9590337	54.948587231	1.4755500320	2.6534053225	3.9320964	1.9829514	3.9659028	2.4155	3.2586	1.8051592	3.6103185
DOUTER	2.3155	0.7000000	0.7678660	0.6952930	1.3905860	79.674710	0.9838060	56.367932926	1.8494741809	2.5435562095	4.5029780	2.1220221	4.2440443	2.3155	3.7317	1.9317608	3.8635217
6.625	2.2155	0.8000000	0.7347040	0.7455660	1.4911320	85.435574	0.9968284	57.114064851	2.2474106420	2.4337070966	5.0497260	2.2471595	4.4943190	2.2155	4.1848	2.0456783	4.0913567
	2.1155	0.9000000	0.7015420	0.7932372	1.5864745	90.898294	0.9998770	57.288737840	2.6670356432	2.3238579837	5.5723403	2.3605805	4.7211610	2.1155	4.6179	2.1489299	4.2978599
	2.0155	1	0.6683800	0.8387675	1.6775351	96.115683	0.9943088	56.969698835	3.1063705766	2.2140088708	6.0708209	2.4639036	4.9278072	2.0155	5.031	2.2429890	4.4859781
	1.9155	1.1	0.6352180	0.8825055	1.7650110	101.12768	0.9811995	56.218591762	3.5636932520	2.1041597579	6.5451679	2.5583525	5.1167051	1.9155	5.4241	2.3289697	4.6579394
	1.8155	1.2	0.6020560	0.9247226	1.8494453	105.96541	0.9614279	55.085761502	4.0374780014	1.9943106450	6.9953813	2.6448783	5.2897566	1.8155	5.7972	2.4077375	4.8154750
	1.7155	1.3	0.5688940	0.9656358	1.9312717	110.65371	0.9357292	53.613336458	4.5263535198	1.8844615320	7.4214609	2.7242358	5.4484717	1.7155	6.1503	2.4799798	4.9599596
	1.6155	1.4	0.5357320	1.0054218	2.0108437	115.21285	0.9047314	51.837295270	5.0290721569	1.7746124191	7.8234070	2.7970353	5.5940707	1.6155	6.4834	2.5462521	5.0925042
	1.5155	1.5	0.5025700	1.0442273	2.0884547	119.65964	0.8689803	49.788903713	5.5444869051	1.6647633062	8.2012193	2.8637771	5.7275542	1.5155	6.7965	2.6070097	5.2140195
	1.4155	1.6	0.4694080	1.0821760	2.1643521	124.00824	0.8289571	47.495744810	6.0715337295	1.5549141933	8.5548981	2.9248757	5.8497514	1.4155	7.0896	2.6626302	5.3252605
	1.3155	1.7	0.4362460	1.1193737	2.2387474	128.27078	0.7850923	44.982477089	6.6092177120	1.4450650804	8.8844431	2.9806783	5.9613566	1.3155	7.3627	2.7134295	5.4268591
	1.2155	1.8	0.4030840	1.1559120	2.3118240	132.45775	0.7377752	42.271405767	7.1566019813	1.3352159675	9.1898545	3.0314772	6.0629545	1.2155	7.6158	2.7596738	5.5193477
	1.1155	1.9	0.3699220	1.1918711	2.3837423	136.57837	0.6873616	39.382921976	7.7127987184	1.2253668545	9.4711323	3.0775204	6.1550409	1.1155	7.8489	2.8015888	5.6031776
	1.0155	2	0.3367600	1.2273224	2.4546449	140.64079	0.6341801	36.335846909	8.2769617351	1.1155177416	9.7282764	3.1190185	6.2380370	1.0155	8.062	2.8393661	5.6787322
	0.9154999	2.1	0.3035980	1.2623296	2.5246592	144.65231	0.5785366	33.147706161	8.8482802606	1.0056686287	9.9612868	3.1561506	6.3123012	0.9154999	8.2551	2.8731689	5.7463379
	0.8154999	2.2	0.2704360	1.2969503	2.5939007	148.61956	0.5207181	29.834952053	9.4259736678	0.8958195158	10.170163	3.1890694	6.3781388	0.8154999	8.4282	2.9031362	5.8062724
	0.7154999	2.3	0.2372740	1.3312374	2.6624749	152.54857	0.4609963	26.413146676	10.009286936	0.7859704029	10.354906	3.2179040	6.4358081	0.7154999	8.5813	2.9293856	5.8587712
	0.6154999	2.4	0.2041120	1.3652397	2.7304794	156.44494	0.3996300	22.897114982	10.597486697	0.6761212900	10.515516	3.2427636	6.4855273	0.6154999	8.7144	2.9520162	5.9040325
	0.5154999	2.5	0.1709500	1.3990024	2.7980049	160.31387	0.3368673	19.301074861	11.189857739	0.5662721770	10.651992	3.2637389	6.5274779	0.5154999	8.8275	2.9711109	5.9422218
	0.4154999	2.6	0.1377880	1.4325684	2.8651369	164.16025	0.2729476	15.638749513	11.785699876	0.4564230641	10.764334	3.2809044	6.5618089	0.4154999	8.9206	2.9867373	5.9734747
	0.3154999	2.7	0.1046260	1.4659783	2.9319567	167.98875	0.2081037	11.923466187	12.384325108	0.3465739512	10.852542	3.2943197	6.5886395	0.3154999	8.9937	2.9989498	5.9978996
	0.2154999	2.8	0.0714641	1.4992712	2.9985425	171.80383	0.1425627	8.1682445494	12.985055002	0.2367248383	10.916617	3.3040305	6.6080610	0.2154999	9.0468	3.0077898	6.0155797
	0.1154999	2.9	0.0383021	1.5324848	3.0649696	175.60982	0.0765479	4.3858773184	13.587218240	0.1268757254	10.956558	3.3100693	6.6201386	0.1154999	9.0799	3.0132872	6.0265744
	0.0154999	3	0.0051401	1.5656561	3.1313123	179.41098	0.0102800	0.5890053725	14.190148295	0.0170266125	10.972366	3.3124562	6.6249124	0.0154999	9.093	3.0154601	6.0309203

Horizonta Blinds L = 3' = 36"	VID (cubic inches [radians])	aOUTER (Chord Length)	Window Height/aC	Number of Blinds Required	Number of Blinds for Available Energy	VTOTAL (cubic inches [radians	Available Energy per Louver (KJ/louver)	Available Energy of All Louvers (KJ)	Available Energy of All Louvers (kWh)	Blackbody Surface Area	sINNER	Reflective Surface Area	Total Surface Area	Available PCM Mass	Mass/Tota Surface Area	Mass/Blac Surface Area	Mass/Refle Surface Area
	3.7090588	1.6919616	49.646515	50	49	181.74388	8.5335608792	418.14448308	0.1161605373	55.449349	1.5575148	56.070534	111.51988	141.76023	1.2711655	2.5565715	2.52824824
	10.437883	2.3725374	35.405131	36	35	365.32593	24.014802349	840.51808224	0.2334959232	77.753333	2.2088678	79.519242	157.27257	284.95422	1.8118494	3.6648490	3.58346251
	19.077804	2.8807288	29.159287	30	29	553.25634	43.892969651	1272.8961199	0.3536105421	94.407897	2.7130221	97.668796	192.07669	431.53994	2.2467064	4.5710153	4.41840138

6-Inch

		29.220678	3.2972305	25.475925	26	25	730.51696	67.229032064	1680.7258016	0.4669056276	108.05758	3.1417856	113.10428	221.16186	569.80323	2.5764081	5.27314425.0378571
		40.624049	3.6535359	22.991425	23	22	893.72908	93.465164490	2056.2336187	0.5712216992	119.73450	3.5229117	126.82482	246.55932	697.10869	2.8273466	5.8221202	5.4966266
		53.119801	3.9659028	21.180548	22	21	1115.5158	122.21457507	2566.5060766	0.7129753881	129.97146	3.8706100	139.34196	269.31342	870.10234	3.2308167	6.6945642	6.2443670
		66.581070	4.2440443	19.792441	20	19	1265.0403	153.18538595	2910.5223331	0.8085431041	139.08678	4.1933121	150.95923	290.04602	986.73146	3.4019824	7.0943583	6.5364099
		80.906783	4.4943190	18.690261	19	18	1456.3220	186.14505146	3350.6109263	0.9307997153	147.28884	4.4965087	161.87431	309.16315	1135.9312	3.6742128	7.7122693	7.0173655
		96.013283	4.7211610	17.792233	18	17	1632.2258	220.90110182	3755.3187309	1.0432275434	154.72295	4.7840139	172.22450	326.94745	1273.1361	3.8940083	8.2284888	7.3923055
		111.82934	4.9278072	17.046121	18	17	1901.0987	257.28965594	4373.9241511	1.2150761291	161.49521	5.0586072	182.10986	343.60507	1482.8570	4.3155854	9.1820495	8.1426511
		128.29295	5.1167051	16.416814	17	16	2052.6873	295.16807093	4722.6891349	1.3119630416	167.68582	5.3223908	191.60606	359.29189	1601.0961	4.4562545	9.5481901	8.3561867
		145.34920	5.2897566	15.879747	16	15	2180.2381	334.40998112	5016.1497168	1.3934863913	173.35710	5.5770024	200.77208	374.12919	1700.5857	4.5454505	9.8097263	8.4702298
		162.94872	5.4484717	15.417167	16	15	2444.2309	374.90180616	5623.5270925	1.5622158262	178.55854	5.8237499	209.65499	388.21354	1906.5001	4.9109571	10.677170	9.0935113
		181.04659	5.5940707	15.015898	16	15	2715.6989	416.54020763	6248.1031145	1.7357230452	183.33015	6.0636992	218.29317	401.62332	2118.2451	5.2742085	11.554265	9.7036713
		199.60152	5.7275542	14.665945	15	14	2794.4214	459.23018295	6429.2225613	1.7860380275	187.70470	6.2977351	226.71846	414.42317	2179.6486	5.2594759	11.612115	9.6139001
		218.57521	5.8497514	14.359584	15	14	3060.0529	502.88360187	7040.3704262	1.9558149044	191.70938	6.5266038	234.95773	426.66711	2386.8413	5.5941534	12.450310	10.158598
		237.93183	5.9613566	14.090752	15	14	3331.0457	547.41805887	7663.8528242	2.1290183145	195.36692	6.7509429	243.03394	438.40087	2598.2156	5.9265749	13.299158	10.690752
		257.63767	6.0629545	13.854631	14	13	3349.2897	592.75595621	7705.8274308	2.1406788602	198.69652	6.9713053	250.96699	449.66351	2612.4459	5.8097797	13.147920	10.409520
		277.66075	6.1550409	13.647350	14	13	3609.5898	638.82375901	8304.7088671	2.3070481232	201.71439	7.1881751	258.77430	460.48870	2815.4800	6.1141131	13.957754	10.880060
		297.97062	6.2380370	13.465774	14	13	3873.6180	685.55138048	8912.1679462	2.4758002554	204.43436	7.4019817	266.47134	470.90570	3021.4221	6.4161934	14.779424	11.338638
		318.53808	6.3123012	13.307349	14	13	4140.9951	732.87166736	9527.3316757	2.6466927395	206.86816	7.6131099	274.07195	480.94012	3229.9762	6.7159633	15.613693	11.785139
		339.33505	6.3781388	13.169986	14	13	4411.3556	780.71996309	10149.359520	2.8194920747	209.02580	7.8219076	281.58867	490.61448	3440.8574	7.0133629	16.461399	12.219445
		360.33432	6.4358081	13.051973	14	13	4684.3462	829.03373201	10777.438516	2.9939724198	210.91576	8.0286933	289.03295	499.94872	3653.7901	7.3083297	17.323456	12.641430
		381.50952	6.4855273	12.951915	13	12	4578.1142	877.75223176	10533.026781	2.9260748398	212.54517	8.2337607	296.41538	508.96055	3570.9291	7.0161215	16.800801	12.047043
		402.83487	6.5274779	12.868676	13	12	4834.0185	926.81622387	11121.794686	3.0896345639	213.91998	8.4373837	303.74581	517.66580	3770.5344	7.2837233	17.625910	12.413453
		424.28519	6.5618089	12.801347	13	12	5091.4223	976.16771450	11714.012574	3.2541526930	215.04508	8.6398204	311.03353	526.07862	3971.3094	7.5488895	18.467333	12.768106
		445.83570	6.5886395	12.749217	13	12	5350.0284	1025.7497190	12308.996628	3.4194392634	215.92438	8.8413157	318.28736	534.21175	4173.0221	7.8115506	19.326312	13.110863
		467.46198	6.6080610	12.711747	13	12	5609.5437	1075.5060452	12906.072543	3.5853069525	216.56087	9.0421049	325.51577	542.07664	4375.4441	8.0716336	20.204222	13.441573
		489.13985	6.6201386	12.688556	13	12	5869.6782	1125.3810903	13504.573083	3.7515704026	216.95668	9.2424161	332.72698	549.68366	4578.3490	8.3290615	21.102595	13.760077
		510.84533	6.6249124	12.679412	13	12	6130.1440	1175.3196479	14103.835775	3.9180455785	217.11313	9.4424725	339.92901	557.04214	4781.5123	8.5837533	22.023137	14.066208

	Vertical Blinds L = 7' = 84"	VID (cubic inches [radians	aOUTER (Chord Length)	Window Height/aC	Number of Blinds Required	Number of Blinds for Available Energy	VTOTAL (cubic inches [radians	Available Energy per Louver (KJ/louver)	Available Energy of All Louvers (KJ)	Available Energy of All Louvers (kWh)	Blackbody Surface Area	sINNER	Reflective Surface Area	Total Surface Area	Available PCM Mass	Mass/Total Surface Area	Mass/Black Surface Area	Mass/Reflect Surface Area
		8.6544707	1.691961	21.277078	22	21	181.74388	19.911642051	418.14448308	0.1161605373	129.38181	1.5575148	130.83124	260.21306	141.76023	0.5447852	1.0956735	1.0835349
		24.355062	2.372537	15.173627	16	15	365.32593	56.034538816	840.51808224	0.2334959232	181.42444	2.2088678	185.54489	366.96934	284.95422	0.7765068	1.5706495	1.5357696
		44.514878	2.880728	12.496837	13	12	534.17853	102.41692918	1229.0031502	0.3414170751	220.28509	2.7130221	227.89385	448.17895	416.65925	0.9296716	1.8914546	1.8283040
		68.181583	3.297230	10.918253	11	10	681.81583	156.86774148	1568.6774148	0.4357785858	252.13436	3.1417856	263.90999	516.04436	531.81634	1.0305632	2.1092577	2.0151428
		94.789448	3.653535	9.8534682	10	9	853.10504	218.08538381	1962.7684542	0.5452570766	279.38051	3.5229117	295.92458	575.30509	665.42193	1.1566418	2.3817764	2.2486199
		123.94620	3.965902	9.0773780	10	9	1115.5158	285.16734185	2566.5060766	0.7129753881	303.26675	3.8706100	325.13124	628.39799	870.10234	1.3846357	2.8690989	2.6761572
		155.35583	4.244044	8.4824750	9	8	1242.8466	357.43256722	2859.4605378	0.7943581374	324.53582	4.1933121	352.23822	676.77404	969.42038	1.4324136	2.9870982	2.7521726
		188.78249	4.494319	8.0101121	9	8	1510.2599	434.33845341	3474.7076273	0.9652737788	343.67396	4.4965087	377.70673	721.38070	1178.0027	1.6329834	3.4276752	3.1188291
		224.03099	4.721161	7.6252430	8	7	1568.2169	515.43590425	3608.0513297	1.0023166594	361.02023	4.7840139	401.85716	762.87740	1223.2092	1.6034152	3.3882013	3.0438905
		260.93512	4.927807	7.3054806	8	7	1826.5458	600.34253054	4202.3977138	1.1674260848	376.82216	5.0586072	424.92300	801.74517	1424.7058	1.7770057	3.7808439	3.3528563
		299.35023	5.116705	7.0357776	8	7	2095.4516	688.72549884	4821.0784919	1.3392956050	391.26691	5.3223908	447.08082	838.34774	1634.4522	1.9496113	4.1773332	3.6558317
		339.14815	5.289756	6.8056061	7	6	2034.8889	780.28995595	4681.7397357	1.3005872985	404.49990	5.5770024	468.46820	872.96811	1587.2133	1.8181802	3.9238905	3.3880919
		380.21369	5.448471	6.6073574	7	6	2281.2821	874.77088105	5248.6252863	1.4580681045	416.63661	5.8237499	489.19499	905.83160	1779.4000	1.9643828	4.2708682	3.6374045
		422.44206	5.594070	6.4353851	7	6	2534.6523	971.92715115	5831.5629069	1.6200081755	427.77036	6.0636992	509.35073	937.12109	1977.0288	2.1096834	4.6217060	3.8814685

6-Inch

		465.73690	5.727554	6.2854053	7	6	2794.4214	1071.5370935	6429.2225613	1.7860380275	437.97764	6.2977351	529.00975	966.98739	2179.6486	2.2540611	4.9766208	4.12024290
		510.00883	5.849751	6.1541075	7	6	3060.0529	1173.3950710	7040.3704262	1.9558149044	447.32188	6.5266038	548.23471	995.55660	2386.8413	2.3974943	5.3358474	4.35368511
		555.17428	5.961356	6.0388938	7	6	3331.0457	1277.3088040	7663.8528242	2.1290183145	455.85616	6.7509429	567.07921	1022.9353	2598.2156	2.5399607	5.6996391	4.58175086
		601.15456	6.062954	5.9376991	6	5	3005.7728	1383.0972311	6915.4861558	1.9211220541	463.62521	6.9713053	585.58964	1049.2148	2344.5028	2.2345306	5.0568923	4.00366164
		647.87509	6.155040	5.8488644	6	5	3239.3754	1490.5887710	7452.9438551	2.0704278029	470.66692	7.1881751	603.80671	1074.4736	2526.7128	2.3515819	5.3683671	4.18463858
		695.26478	6.238037	5.7710462	6	5	3476.3239	1599.6198877	7998.0994389	2.2218720241	477.01350	7.4019817	621.76646	1098.7799	2711.5326	2.4677667	5.6843938	4.36101461
		743.25554	6.312301	5.7031498	6	5	3716.2777	1710.0338905	8550.1694526	2.3752370739	482.69238	7.6131099	639.50123	1122.1936	2898.6966	2.5830628	6.0052668	4.53274593
		791.78178	6.378138	5.6442797	6	5	3958.9089	1821.6799138	9108.3995694	2.5303134004	487.72688	7.8219076	657.04024	1144.7671	3087.9489	2.6974472	6.3313076	4.69978666
		840.78010	6.435808	5.5937030	6	5	4203.9005	1934.4120413	9672.0602068	2.6868983254	492.13678	8.0286933	674.41023	1166.5470	3279.0424	2.8108960	6.6628679	4.86208870
		890.18888	6.485527	5.5508207	6	5	4450.9444	2048.0885407	10240.442703	2.8447949831	495.93873	8.2337607	691.63589	1187.5746	3471.7366	2.9233839	7.0003337	5.01960156
		939.94805	6.527477	5.5151469	6	5	4699.7402	2162.5711890	10812.855945	3.0038113815	499.14663	8.4373837	708.74023	1207.8868	3665.7973	3.0348847	7.3441292	5.17227214
		989.99878	6.561808	5.4862919	6	5	4949.9939	2277.7246671	11388.623335	3.1637595627	501.77187	8.6398204	725.74491	1227.5167	3860.9952	3.1453706	7.6947223	5.32004454
		1040.2833	6.588639	5.4639504	6	5	5201.4165	2393.4160111	11967.080055	3.3244548395	503.82356	8.8413157	742.67052	1246.4940	4057.1049	3.2548127	8.0526302	5.46285976
		1090.7446	6.608061	5.4478915	6	5	5453.7231	2509.5141056	12547.570528	3.4857150927	505.30870	9.0421049	759.53681	1264.8455	4253.9040	3.3631806	8.4184262	5.60065547
		1141.3263	6.620138	5.4379526	6	5	5706.6316	2625.8892107	13129.446053	3.6473601136	506.23225	9.2424161	776.36295	1282.5952	4451.1726	3.4704423	8.7927480	5.73336564
		1191.9724	6.624912	5.4340340	6	5	5959.8622	2742.4125119	13712.062559	3.8092109791	506.59730	9.4424725	793.16769	1299.7649	4648.6925	3.5765639	9.1763073	5.86092025

12

Incremen
*See atta

	rINNER (Height of Triangular Portion)	hINNER (Height of Arced Portion)	rINNER/RI	cos-1 (r/R)	theta (Central Angle [Radians]	theta (Central Angle [Degrees]	sin (theta) [Radians]	sin(theta) [Degrees]	AID (square inches [radians])	rOUTER	R2OUTER - r2OUTER	SQRT (R2OUTER - r2OUTER)	aOUTER (Chord Length)	rINNER	R2INNER - r2INNER	SQRT (R2INNER - r2INNER)	aINNER (Chord Length)
RINNER	3.871	0.1	0.9748174	0.2248954	0.4497909	25.771120	0.4347772	24.910901485	0.1183740081	4.203900151	0.9248797	0.9617066	1.9234133	3.871	0.7842	0.8855506	1.7711013
3.971	3.771	0.2	0.9496348	0.3187277	0.6374555	36.523511	0.5951526	34.099732150	0.3335340714	4.0953003021	1.8261716	1.3513591	2.7027183	3.771	1.5484	1.2443472	2.4886944
ROUTER	3.671	0.3	0.9244522	0.3911997	0.7823994	44.828184	0.7049831	40.392560346	0.6103822366	3.9867004532	2.7038757	1.6443466	3.2886932	3.671	2.2926	1.5141334	3.0282668
4.3125	3.571	0.4	0.8992697	0.4526993	0.9053986	51.875522	0.7866713	45.072947976	0.9360961568	3.8781006043	3.5579919	1.8862640	3.7725280	3.571	3.0168	1.7368937	3.4737875
DINNER	3.471	0.5	0.8740871	0.5072429	1.0144858	58.125757	0.8492091	48.656100811	1.3031108698	3.7695007554	4.3885203	2.0948795	4.1897590	3.471	3.721	1.9289893	3.8579787
7.942	3.371	0.6	0.8489045	0.5568870	1.1137741	63.814555	0.8973705	51.415542406	1.7062170034	3.6609009065	5.1954608	2.2793553	4.5587106	3.371	4.4052	2.0988568	4.1977136
DOUTER	3.271	0.7000000	0.8237219	0.6028518	1.2057037	69.081733	0.9340906	53.519454513	2.1415111665	3.5523010576	5.9788134	2.4451612	4.8903224	3.271	5.0694	2.2515328	4.5030656
8.625	3.171	0.8000000	0.7985394	0.6459314	1.2918629	74.018296	0.9613496	55.081278527	2.6059059255	3.4437012087	6.7385782	2.5958771	5.1917543	3.171	5.7136	2.3903137	4.7806275
	3.071	0.9000000	0.7733568	0.6866772	1.3733544	78.687411	0.9805715	56.182613196	3.0968649500	3.3351013598	7.4747551	2.7339998	5.4679996	3.071	6.3378	2.5174987	5.0349975
	2.971	1	0.7481742	0.7254901	1.4509803	83.135053	0.9928306	56.885006286	3.6122452353	3.2265015109	8.1873442	2.8613535	5.7227071	2.971	6.942	2.6347675	5.2695350
	2.871	1.1	0.7229916	0.7626733	1.5253467	87.395929	0.9989673	57.236612690	4.1501962962	3.1179016620	8.8763454	2.9793196	5.9586392	2.871	7.5262	2.7433920	5.4867841
	2.771	1.2	0.6978091	0.7984620	1.5969241	91.497015	0.9996586	57.276223730	4.7090922515	3.0093018131	9.5417588	3.0889737	6.1779475	2.771	8.0904000	2.8443628	5.6887256
	2.671	1.3	0.6726265	0.8330437	1.6660875	95.459784	0.9954632	57.035841538	5.2874841179	2.9007019642	10.183584	3.1911728	6.3823457	2.671	8.6346000	2.9384689	5.8769379
	2.571	1.4	0.6474439	0.8665705	1.7331411	99.301671	0.9868510	56.542397357	5.8840651482	2.7921021153	10.801822	3.2866125	6.5732250	2.571	9.1588000	3.0263509	6.0527018
	2.471	1.5	0.6222613	0.8991681	1.7983362	103.03707	0.9742242	55.818940530	6.4976449344	2.6835022664	11.396471	3.3758660	6.7517321	2.471	9.6630000	3.1085366	6.2170732
	2.371	1.6	0.5970788	0.9309417	1.8618834	106.67806	0.9579324	54.885486498	7.1271295973	2.5749024175	11.967533	3.4594123	6.9188246	2.371	10.1472	3.1854669	6.3709339
	2.271	1.7	0.5718962	0.9619807	1.9239615	110.23487	0.9382826	53.759637425	7.7715063234	2.4663025686	12.515007	3.5376557	7.0753114	2.271	10.6114	3.2575143	6.5150287
	2.171	1.8	0.5467136	0.9923619	1.9847239	113.71630	0.9155481	52.457046649	8.4298310824	2.3577027197	13.038894	3.6109408	7.2218817	2.171	11.0556	3.3249962	6.6499924
	2.071	1.9	0.5215311	1.0221518	2.0443037	117.12997	0.8899743	50.991773117	9.1012187185	2.2491028708	13.539192	3.6795641	7.3591283	2.071	11.4798	3.3881853	6.7763707
	1.971	2	0.4963485	1.0514088	2.1028176	120.48257	0.8617834	49.376556573	9.7848348473	2.1405030219	14.015903	3.7437819	7.4875638	1.971	11.884	3.4473177	6.8946355
	1.871	2.1	0.4711659	1.0801841	2.1603682	123.77998	0.8311787	47.623034532	10.479889147	2.0319031730	14.469025	3.8038172	7.6076345	1.871	12.2682	3.5025990	7.0051980
	1.771	2.2	0.4459833	1.1085236	2.2170473	127.02745	0.7983470	45.741915747	11.185629743	1.9233033240	14.898560	3.8598653	7.7197307	1.771	12.6324	3.5542087	7.1084175
	1.671	2.3	0.4208008	1.1364684	2.2729368	130.22968	0.7634614	43.743120672	11.901338452	1.8147034751	15.304507	3.9120975	7.8241951	1.671	12.9766	3.6023048	7.2046096
	1.571	2.4	0.3956182	1.1640554	2.3281108	133.39092	0.7266834	41.635896527	12.626326727	1.7061036262	15.686866	3.9606649	7.9213298	1.571	13.3008	3.6470261	7.2940523
	1.471	2.5	0.3704356	1.1913183	2.3826366	136.51502	0.6881643	39.428912580	13.359932162	1.5975037773	16.045637	4.0057006	8.0114013	1.471	13.605	3.6884956	7.3769912
	1.371	2.6	0.3452530	1.2182878	2.4365757	139.60550	0.6480466	37.130339872	14.101515448	1.4889039284	16.380821	4.0473227	8.0946454	1.371	13.8892	3.7268217	7.4536434
	1.271	2.7	0.3200705	1.2449924	2.4899848	142.66562	0.6064655	34.747918553	14.850457715	1.3803040795	16.692416	4.0856354	8.1712708	1.271	14.1534	3.7621004	7.5242009
	1.171	2.8	0.2948879	1.2714580	2.5429161	145.69836	0.5635496	32.289015304	15.606158175	1.2717042306	16.980424	4.1207310	8.2414621	1.171	14.3976	3.7944169	7.5888339
	1.071	2.9	0.2697053	1.2977092	2.5954185	148.70652	0.5194217	29.760672752	16.368032035	1.1631043817	17.244844	4.1526912	8.3053824	1.071	14.6218	3.8238462	7.6476924
	0.9709999	3	0.2445227	1.3237688	2.6475376	151.69273	0.4741998	27.169652369	17.135508619	1.0545045328	17.485676	4.1815877	8.3631755	0.9709999	14.826	3.8504545	7.7009090
	0.8709999	3.1	0.2193402	1.3496581	2.6993163	154.65943	0.4279978	24.522472062	17.908029668	0.9459046839	17.702920	4.2074838	8.4149677	0.8709999	15.0102	3.8742999	7.7485998
	0.7709999	3.2	0.1941576	1.3753976	2.7507952	157.60896	0.3809257	21.825439404	18.685047800	0.8373048350	17.896576	4.2304345	8.4608691	0.7709999	15.1744	3.8954332	7.7908664
	0.6709999	3.3	0.1689750	1.4010066	2.8020132	160.54353	0.3330905	19.084681307	19.466025091	0.7287049861	18.066645	4.2504876	8.5009753	0.6709999	15.3186	3.9138983	7.8277966
	0.5709999	3.4	0.1437924	1.4265036	2.8530072	163.46527	0.2845963	16.306170747	20.250431766	0.6201051372	18.213125	4.2676838	8.5353677	0.5709999	15.4428	3.9297328	7.8594656
	0.4709999	3.5	0.1186099	1.4519065	2.9038130	166.37623	0.2355452	13.495751110	21.037744970	0.5115052883	18.336018	4.2820577	8.5641155	0.4709999	15.547	3.9429684	7.8859368
	0.3709999	3.6	0.0934273	1.4772325	2.9544650	169.27837	0.1860374	10.659158582	21.827447628	0.4029054394	18.435323	4.2936375	8.5872751	0.3709999	15.6312	3.9536312	7.9072624
	0.2709999	3.7	0.0682447	1.5024984	3.0049969	172.17364	0.1361713	7.8020429892	22.619027344	0.2943055905	18.511040	4.3024458	8.6048917	0.2709999	15.6954	3.9617420	7.9234840
	0.1709999	3.8	0.0430622	1.5277208	3.0554416	175.06390	0.0860445	4.9299874069	23.411975364	0.1857057416	18.563169	4.3084996	8.6169993	0.1709999	15.7396	3.9673164	7.9346329
	0.0709999	3.9	0.0178796	1.5529157	3.1058314	177.95103	0.0357535	2.0485268507	24.205785565	0.0771058927	18.591710	4.3118106	8.6236212	0.0709999	15.7638	3.9703652	7.9407304

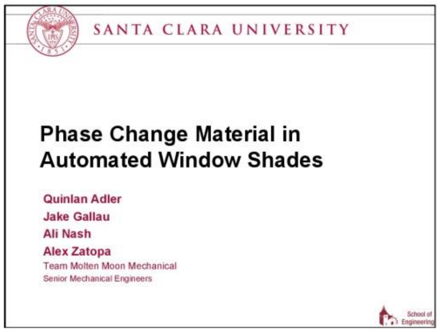
8-Inch

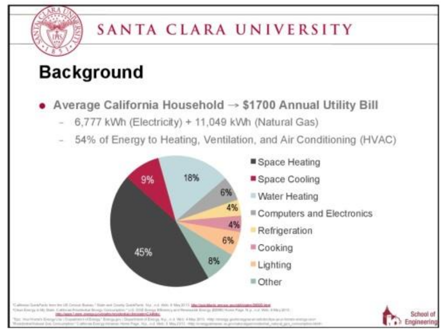
Horizontal Blinds L = 3' = 36"	VID (cubic inches [radians])	aOUTER (Chord Length)	Window Height/aC	Number of Blinds Required	Number of Blinds for Available Energy	VTOTAL (cubic inches [radians	Available Energy per Louver (KJ/louver)	Available Energy of All Louvers (KJ)	Available Energy of All Louvers (kWh)	Blackbody Surface Area	sINNER	Reflective Surface Area	Total Surface Area	Available PCM Mass	Mass/Total Surface Area	Mass/Black Surface Area	Mass/Reflec Surface Area
	4.2614642	1.9234133	43.672358	44	43	183.24296	9.8044991970	421.59346547	0.1171186647	63.759648	1.7861197	64.300309	128.05995	142.92951	1.1161140	2.2416922	2.22284330
	12.007226	2.7027183	31.079819	32	31	372.22402	27.625444026	856.38876481	0.2379047988	89.592999	2.5313359	91.128092	180.72109	290.33473	1.6065348	3.2405962	3.18600697
	21.973760	3.2886932	25.542060	26	25	549.34401	50.555795515	1263.8948878	0.3511099998	109.01760	3.1069080	111.84869	220.86629	428.48833	1.9400349	3.9304507	3.83096418
	33.699461	3.7725280	22.266236	23	22	741.38815	77.533524149	1705.7375312	0.4738538861	125.05635	3.5953381	129.43217	254.48852	578.28276	2.2723333	4.6241774	4.46784405
	46.911991	4.1897590	20.048885	21	20	938.23982	107.93205095	2158.6410190	0.5996704751	138.88723	4.0285232	145.02683	283.91407	731.82706	2.5776357	5.2692176	5.04614920
	61.423812	4.5587106	18.426262	19	18	1105.6286	141.31990210	2543.7582378	0.7066560384	151.11769	4.4227969	159.22069	310.33838	862.39032	2.7788709	5.7067462	5.41632068
	77.094401	4.8903224	17.176781	18	17	1310.6048	177.37377356	3015.3541505	0.8376653830	162.11036	4.7878494	172.36257	334.47294	1022.2717	3.0563661	6.3060235	5.93093802
	93.812613	5.1917543	16.179502	17	16	1501.0018	215.83794414	3453.4071063	0.9593564941	172.10259	5.1299878	184.67956	356.78215	1170.7814	3.2815021	6.8028110	6.33952880
	111.48713	5.4679996	15.362107	16	15	1672.3070	256.50233861	3847.5350792	1.0688452450	181.25991	5.4535903	196.32925	377.58916	1304.3995	3.4545470	7.1962935	6.64393868
	130.04082	5.7227071	14.678367	15	14	1820.5715	299.18945948	4188.6524328	1.1636076458	189.70326	5.7618431	207.42635	397.12961	1420.0458	3.5757742	7.4856163	6.84602424
	149.40706	5.9586392	14.097178	15	14	2091.6989	343.74603764	4812.4445269	1.3368970895	197.52422	6.0571518	218.05746	415.58169	1631.5251	3.9258831	8.2598736	7.48208812
	169.52732	6.1779475	13.596748	14	13	2203.8551	390.03740710	5070.4862923	1.4085810920	204.79412	6.3413858	228.28989	433.08401	1719.0070	3.9692229	8.3938298	7.52993055
	190.34942	6.3823457	13.161305	14	13	2474.5425	437.94355372	5693.2661984	1.5815893499	211.56976	6.6160336	238.17721	449.74697	1930.1432	4.2916201	9.1229632	8.10381142
	211.82634	6.5732250	12.779115	13	12	2541.9161	487.35624427	5848.2749312	1.6246507759	217.89726	6.8823034	247.76292	465.66019	1982.6945	4.2578142	9.0992173	8.00238619
	233.91521	6.7517321	12.441251	13	12	2806.9826	538.17688147	6458.1225776	1.7940664520	223.81463	7.1411931	257.08295	480.89759	2189.4464	4.5528330	9.7824095	8.51649794
	256.57666	6.9188246	12.140790	13	12	3078.9199	590.31486319	7083.7783583	1.9678736279	229.35362	7.3935390	266.16740	495.52103	2401.5575	4.8465300	10.470981	9.02273353
	279.77422	7.0753114	11.872268	12	11	3077.5165	643.68630168	7080.5493185	1.9669766006	234.54103	7.6400511	275.04184	509.58287	2400.4628	4.7106427	10.234724	8.72762802
	303.47391	7.2218817	11.631317	12	11	3338.2131	698.21300626	7680.3430689	2.1335993045	239.39972	7.8813386	283.72819	523.12792	2603.8062	4.9773795	10.876395	9.17711492
	327.64387	7.3591283	11.414395	12	11	3604.0826	753.82166261	8292.0382887	2.3035282366	243.94934	8.1179302	292.24549	536.19483	2811.1844	5.2428413	11.523640	9.61925685
	352.25405	7.4875638	11.218602	12	11	3874.7945	810.44316164	8914.8747780	2.4765522133	248.20688	8.3502887	300.61039	548.81727	3022.3397	5.5070055	12.176696	10.0540096
	377.27600	7.6076345	11.041539	12	11	4150.0361	868.01204383	9548.1324821	2.6524712035	252.18713	8.5788224	308.83760	561.02473	3237.0281	5.7698492	12.835818	10.4813276
	402.68267	7.7197307	10.881208	11	10	4026.8267	926.46603396	9264.6603396	2.5737226423	255.90303	8.8038949	316.94021	572.84325	3140.9248	5.4830441	12.273886	9.91014911
	428.44818	7.8241951	10.735928	11	10	4284.4818	985.74564756	9857.4564756	2.7384014089	259.36594	9.0258321	324.92995	584.29590	3341.8958	5.7195263	12.884867	10.2849729
	454.54776	7.9213298	10.604280	11	10	4545.4776	1045.7938547	10457.938547	2.9052153285	262.58588	9.2449281	332.81741	595.40329	3545.4725	5.9547411	13.502144	10.6529057
	480.95755	8.0114013	10.485057	11	10	4809.5755	1106.5557906	11065.557906	3.0740119865	265.57168	9.4614501	340.61220	606.18388	3751.4689	6.1886648	14.126012	11.0139005
	507.65455	8.0946454	10.377230	11	10	5076.5455	1167.9785037	11679.785037	3.2446442833	268.33116	9.6756424	348.32312	616.65428	3959.7055	6.4212730	14.756785	11.3679088
	534.61647	8.1712708	10.279918	11	10	5346.1647	1230.0107349	12300.107349	3.4169698218	270.87123	9.8877297	355.95827	626.82950	4170.0085	6.6525402	15.394800	11.7148802
	561.82169	8.2414621	10.192366	11	10	5618.2169	1292.6027234	12926.027234	3.5908503658	273.19802	10.097920	363.52512	636.72314	4382.2092	6.8824405	16.040413	12.0547629
	589.24915	8.3053824	10.113923	11	10	5892.4915	1355.7060328	13557.060328	3.7661513592	275.31692	10.306407	371.03065	646.34758	4596.1433	7.1109469	16.694009	12.3875030
	616.87831	8.3631755	10.044031	11	10	6168.7831	1419.2733958	14192.733958	3.9427414936	277.23272	10.513371	378.48138	655.71411	4811.6508	7.3380314	17.355998	12.7130447
	644.68906	8.4149677	9.9822129	10	9	5802.2016	1483.2585740	13349.327166	3.7084430868	278.94959	10.718985	385.88346	664.83305	4525.7172	6.8072987	16.224139	11.7281969
	672.66172	8.4608691	9.9280579	10	9	6053.9554	1547.6162296	13928.546067	3.8693500974	280.47119	10.923408	393.24269	673.71388	4722.0852	7.0090366	16.836257	12.0080687
	700.77690	8.5009753	9.8812191	10	9	6306.9921	1612.3018084	14510.716276	4.0310769815	281.80067	11.126794	400.56460	682.36528	4919.4538	7.2094140	17.457210	12.2812993
	729.01554	8.5353677	9.8414036	10	9	6561.1398	1677.2714308	15095.442877	4.1935140314	282.94076	11.329291	407.85451	690.79527	5117.6891	7.4084020	18.087493	12.5478301
	757.35881	8.5641155	9.8083684	10	9	6816.2293	1742.4817908	15682.336117	4.3565529734	283.89372	11.531041	415.11749	699.01122	5316.6589	7.6059707	18.727637	12.8076001
	785.78811	8.5872751	9.7819155	10	9	7072.0930	1807.8900607	16271.010546	4.5200867298	284.66144	11.732180	422.35850	707.01995	5516.2325	7.8020889	19.378221	13.0605456
	814.28498	8.6048917	9.7618892	10	9	7328.5648	1873.4538007	16861.084206	4.6840091925	285.24542	11.932842	429.58234	714.82776	5716.2805	7.9967243	20.039867	13.3066004
	842.83111	8.6169993	9.7481729	10	9	7585.4800	1939.1308725	17452.177852	4.8482150074	285.64678	12.133158	436.79371	722.44049	5916.6744	8.1898432	20.713253	13.5456950
	871.40828	8.6236212	9.7406875	10	9	7842.6745	2004.8793556	18043.914200	5.0125993650	285.86629	12.333256	443.99724	729.86354	6117.2861	8.3814107	21.399116	13.7777568

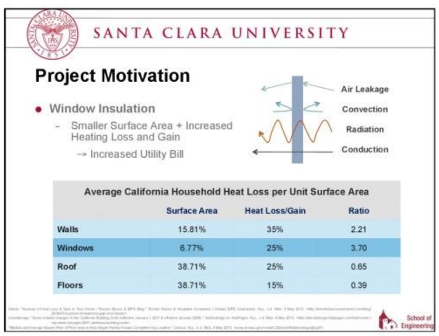
8-Inch

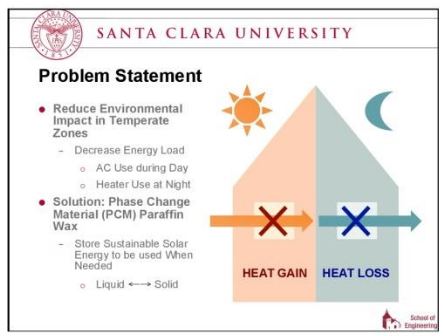
	Vertical Blinds L = 7' = 84"	VID (cubic inches [radians	aOUTER (Chord Length)	Window Height/aC	Number of Blinds Required	Number of Blinds for Available Energy	VTOTAL (cubic inches [radians	Available Energy per Louver (KJ/louver)	Available Energy of All Louvers (KJ)	Available Energy of All Louvers (kWh)	Blackbody Surface Area	sINNER	Reflective Surface Area	Total Surface Area	Available PCM Mass	Mass/Total Surface Area	Mass/Black Surface Area	Mass/Reflect Surface Area
		9.9434166	1.923413	18.716725	19	18	178.98150	22.877164793	411.7889662	0.1143949748	148.77251	1.7861197	150.03405	298.80656	139.60557	0.4672105	0.9383828	0.93049254
		28.016862	2.702718	13.319922	14	13	364.21920	64.459369394	837.9718021	0.2327885666	209.05033	2.5313359	212.63221	421.68254	284.09098	0.6737081	1.3589597	1.33606744
		51.272107	3.288693	10.946597	11	10	512.72107	117.96352286	1179.635228	0.3277026665	254.37441	3.1069080	260.98027	515.35469	399.92244	0.7760139	1.5721802	1.53238567
		78.632077	3.772528	9.5426726	10	9	707.68869	180.91155634	1628.204007	0.4523150731	291.79815	3.5953381	302.00840	593.80655	551.99718	0.9295909	1.8917089	1.82775438
		109.46131	4.189759	8.5923794	9	8	875.69050	251.84145222	2014.731617	0.5596924434	324.07021	4.0285232	338.39595	662.46617	683.03859	1.0310542	2.1076870	2.01845968
		143.32222	4.558710	7.8969696	8	7	1003.2555	329.74643823	2308.225067	0.6412249237	352.60794	4.4227969	371.51494	724.12289	782.53936	1.0806720	2.2192902	2.10634693
		179.88693	4.890322	7.3614777	8	7	1259.2085	413.87213830	2897.104968	0.8048157601	378.25751	4.7878494	402.17934	780.43686	982.18268	1.2585037	2.5965979	2.44215094
		218.89609	5.191754	6.9340723	7	6	1313.3765	503.62186967	3021.731218	0.8394369323	401.57271	5.1299878	430.91898	832.49169	1024.4337	1.2305633	2.5510541	2.37732330
		260.13665	5.467999	6.5837604	7	6	1560.8199	598.50545676	3591.032740	0.9975888953	422.93979	5.4535903	458.10158	881.04138	1217.4395	1.3818188	2.8785174	2.65757547
		303.42859	5.722707	6.2907290	7	6	1820.5715	698.10873880	4188.652432	1.1636076458	442.64094	5.7618431	483.99482	926.63577	1420.0458	1.5324746	3.2081212	2.93401038
		348.61648	5.958639	6.0416478	7	6	2091.6989	802.07408782	4812.444526	1.3368970895	460.88986	6.0571518	508.80075	969.69061	1631.5251	1.6825213	3.5399458	3.20660919
		395.56374	6.177947	5.8271780	6	5	1977.8187	910.08728324	4550.436416	1.2641112364	477.85295	6.3413858	532.67641	1010.5293	1542.6986	1.5266242	3.2283960	2.89612713
		444.14866	6.382345	5.6405593	6	5	2220.7433	1021.8682920	5109.341460	1.4193750576	493.66279	6.6160336	555.74682	1049.4096	1732.1797	1.6506231	3.5088320	3.11685054
		494.26147	6.573225	5.4767636	6	5	2471.3073	1137.1645699	5685.822849	1.5795215876	508.42695	6.8823034	578.11348	1086.5404	1927.6197	1.7740892	3.7913405	3.33432758
		545.80217	6.751732	5.3319650	6	5	2729.0108	1255.7460567	6278.730283	1.7442312728	522.23415	7.1411931	599.86022	1122.0943	2128.6284	1.8970137	4.0760039	3.54854080
		598.67888	6.918824	5.2031958	6	5	2993.3944	1377.4013474	6887.006737	1.9132104716	535.15845	7.3935390	621.05728	1156.2157	2334.8476	2.0193875	4.3629090	3.75947230
		652.80653	7.075311	5.0881152	6	5	3264.0326	1501.9347039	7509.673519	2.0861873037	547.26241	7.6400511	641.76429	1189.0267	2545.9454	2.1412012	4.6521474	3.96710364
		708.10581	7.221881	4.9848503	5	4	2832.4232	1629.1636812	6516.654725	1.8103266826	558.59936	7.8813386	662.03244	1220.6318	2209.2901	1.8099562	3.9550530	3.33713269
		764.50237	7.359128	4.8918836	5	4	3058.0094	1758.9172127	7035.668851	1.9545088068	569.21513	8.1179302	681.90614	1251.1212	2385.2474	1.9064877	4.1904145	3.49791158
		821.92612	7.487563	4.8079723	5	4	3287.7045	1891.0340438	7564.136175	2.1013170295	579.14939	8.3502887	701.42425	1280.5736	2564.4095	2.0025474	4.4278895	3.65600349
		880.31068	7.607634	4.7320885	5	4	3521.2427	2025.3614356	8101.445742	2.2505816272	588.43663	8.5788224	720.62108	1309.0577	2746.5693	2.0981269	4.6675702	3.81139187
		939.59289	7.719730	4.6633751	5	4	3758.3715	2161.7540792	8647.016317	2.4021411328	597.10707	8.8038949	739.52717	1336.6342	2931.5298	2.1932176	4.9095547	3.96405964
		999.71242	7.824195	4.6011122	5	4	3998.8497	2300.0731776	9200.292710	2.5558413149	605.18720	9.0258321	758.16990	1363.3571	3119.1027	2.2878105	5.1539469	4.11398918
		1060.6114	7.921329	4.5446914	5	4	4242.4457	2440.1856611	9760.742644	2.7115343066	612.70039	9.2449281	776.57396	1389.2743	3309.1077	2.3818964	5.4008577	4.26116230
		1122.2343	8.011401	4.4935958	5	4	4488.9372	2581.9635116	10327.85404	2.8690778541	619.66726	9.4614501	794.76181	1414.4290	3501.3710	2.4754659	5.6504050	4.40556022
		1184.5272	8.094645	4.4473843	5	4	4738.1091	2725.2831754	10901.13270	3.0283346645	626.10604	9.6756424	812.75396	1438.8600	3695.7251	2.5685092	5.9027143	4.54716352
		1247.4384	8.171270	4.4056794	5	4	4989.7537	2870.0250483	11480.10019	3.1891718336	632.03288	9.8877297	830.56929	1462.6021	3892.0079	2.6610161	6.1579200	4.68595210
		1310.9172	8.241462	4.3681569	5	4	5243.6691	3016.0730214	12064.29208	3.3514603414	637.46204	10.097920	848.22529	1485.6873	4090.0619	2.7529762	6.4161653	4.82190519
		1374.9146	8.305382	4.3345384	5	4	5499.6587	3163.3140766	12653.25630	3.5150746019	642.40616	10.306407	865.73819	1508.1443	4289.7338	2.8443787	6.6776037	4.95500122
		1439.3827	8.363175	4.3045849	5	4	5757.5308	3311.6379236	13246.55169	3.6798920607	646.87635	10.513371	883.12324	1529.9996	4490.8740	2.9352125	6.9423994	5.08521788
		1504.2744	8.414967	4.2780912	5	4	6017.0979	3460.9366727	13843.74669	3.8457928308	650.88238	10.718985	900.39474	1551.2771	4693.3364	3.0254661	7.2107288	5.21253197
		1569.5440	8.460869	4.2548819	5	4	6278.1760	3611.1045359	14444.41814	4.0126593603	654.43278	10.923408	917.56628	1571.9990	4896.9773	3.1151273	7.4827812	5.33691944
		1635.1461	8.500975	4.2348082	5	4	6540.5844	3762.0375530	15048.15021	4.1803761290	657.53491	11.126794	934.65075	1592.1856	5101.6558	3.2041840	7.7587603	5.45835525
		1701.0362	8.535367	4.2177444	5	4	6804.1450	3913.6333386	15654.53335	4.3488293659	660.19511	11.329291	951.66052	1611.8556	5307.2331	3.2926231	8.0388858	5.57681338
		1767.1705	8.564115	4.2035864	5	4	7068.6823	4065.7908452	16263.16338	4.5179067872	662.41869	11.531041	968.60749	1631.0261	5513.5722	3.3804314	8.3233946	5.69226671
		1833.5056	8.587275	4.1922495	5	4	7334.0224	4218.4101417	16873.64056	4.6874973494	664.21004	11.732180	985.50318	1649.7132	5720.5374	3.4675950	8.6125428	5.80468697
		1899.9982	8.604891	4.1836668	5	4	7599.9931	4371.3922017	17485.56880	4.8574910145	665.57266	11.932842	1002.3587	1667.9314	5927.9946	3.5540996	8.9066078	5.91404465
		1966.6059	8.616999	4.1777883	5	4	7866.4237	4524.6387025	18098.55481	5.0277785262	666.50916	12.133158	1019.1853	1685.6944	6135.8105	3.6399303	9.2058906	6.02030891
		2033.2859	8.623621	4.1745803	5	4	8133.1439	4678.0518298	18712.20731	5.1982511933	667.02135	12.333256	1035.9935	1703.0149	6343.8522	3.7250714	9.5107183	6.12344750

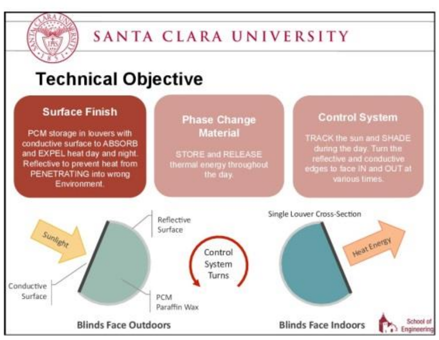
Chapter A.7: Senior Design Conference Presentation Materials

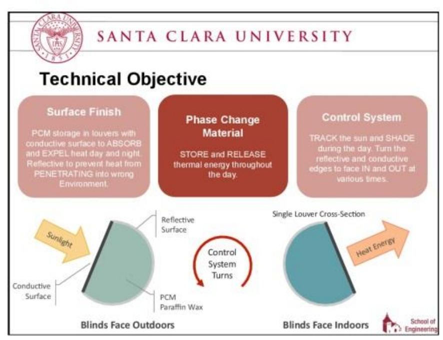


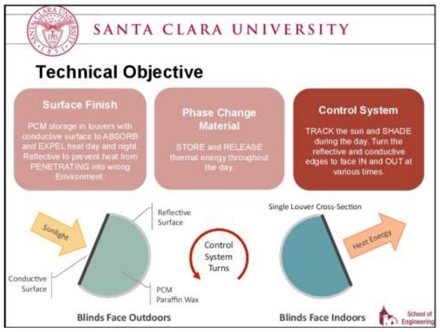











SANTA CLARA UNIVERSITY
Technical Objective
Surface Finish
PCM storage in louvers with conductive surface to ABSORB and EXPEL heat day and night. Reflective to prevent heat from PENETRATING into wrong Environment.
Phase Change Material
STORE and RELEASE thermal energy throughout the day.
Control System
TRACK the sun and SHADE during the day. Turn the reflective and conductive edges to face IN and OUT at various times.
Sunlight
Reflective Surface
Conductive Surface
PCM Paraffin Wax
Control System Turns
Single Louver Cross-Section
Heat Energy
Blinds Face Outdoors
Blinds Face Indoors
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Benchmark
Single-Pane Window + Standard Linen Pleat Blinds
Double-Pane Window + Wood Blinds
Double-Pane Window + Cellular Motorized Shades
Double-Pane Window + PCM Automated Window Shades
$200
$350
$850
<$800
Maximum Heat Loss (R-Value = 3.2)
Median Heat Loss (R-Value = 4.0)
Minimum Heat Loss (R-Value = 6.6)
Heat Source (R-Value = 6.8)
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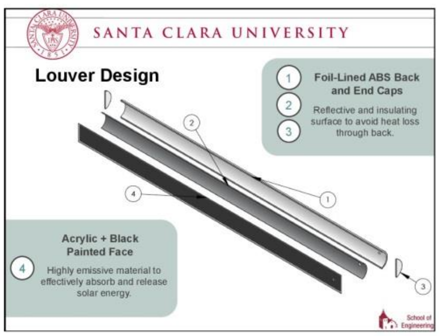
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Louver Design
1 2 3 Foil-Lined ABS Back and End Caps
Reflective and insulating surface to avoid heat loss through back.
4 Acrylic + Black Painted Face
Highly emissive material to effectively absorb and release solar energy.
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Louver Iterations
1
2
Hardware + Waterproofing Seal
3
Two-Part Epoxy
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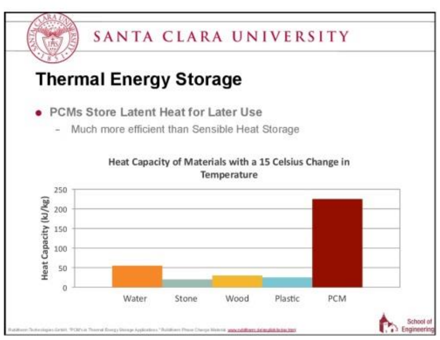
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Thermal Energy Storage
PCMs Store Latent Heat for Later Use
- Much more efficient than Sensible Heat Storage
Heat Capacity of Materials with a 15 Celsius Change in Temperature
Heat Capacity (kJ/kg)
0
50
100
150
200
250
Water
Stone
Wood
Plastic
PCM
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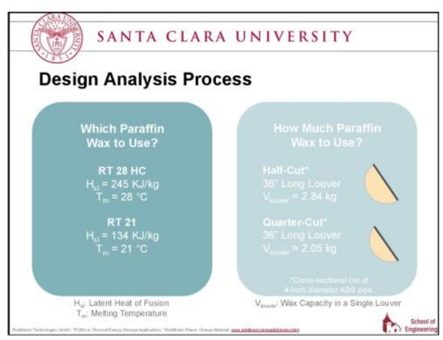
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Design Analysis Process
Which Paraffin Wax to Use?
RT 28 HC
H_{sl} = 245 KJ/kg
T_m = 28 °C
RT 21
H_{sl} = 134 KJ/kg
T_m = 21 °C
How Much Paraffin Wax to Use?
Half-Cut*
36" Long Louver
V_{louver} = 2.84 kg
Quarter-Cut*
36" Long Louver
V_{louver} = 2.05 kg
*Cross-sectional cut of 4-inch diameter ABS pipe.
H_{sl}: Latent Heat of Fusion
T_m: Melting Temperature
V_{louver}: Wax Capacity in a Single Louver
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Design Analysis Process

Which Paraffin Wax to Use?

RT 28 HC
H_{sl} = 245 KJ/kg
T_m = 28 °C

RT 21
H_{sl} = 134 KJ/kg
T_m = 21 °C

H_{sl}: Latent Heat of Fusion
T_m: Melting Temperature

How Much Paraffin Wax to Use?

Half-Cut*
36" Long Louver
V_{louver} = 2.84 kg

Quarter-Cut*
36" Long Louver
V_{louver} = 2.05 kg

*Cross-sectional cut of 4-inch diameter ABS pipe.

V_{louver}: Wax Capacity in a Single Louver

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Theoretical Louver Comparison

	Quarter-Cut Louver	Half-Cut Louver
Available Energy	1.19 kWh	2.44 kWh
Surface Area per Unit Mass	143.95 in²/kg	128.59 in²/kg
Melting Time	4.34 Hours	4.88 Hours
Solidification Time (Without Fan)	18.8 Hours	21.2 Hours
Solidification Time (With Fan)	5.82 Hours	6.54Hours

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Control System Motivation

- Innovative Design
- Current PCM Products Do Not
  - Change Surface Direction
    - Keeps absorptive surface facing out and conductive in during the day, and the opposite at night.
  - Track the Sun
    - Solar tracking allows for more direct radiation and optimized melting and solidifying process.

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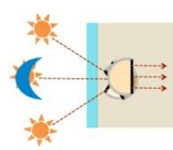
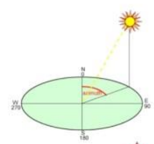
Control System Design

- Louver Direction Dictated by Known Azimuthal Angle of Sun
  - **Arduino Micro-Controller** → Low Cost and Open Source
  - **Servo Motor** → Turn Louvers with Low Energy Consumption
  - **Digital Compass** → Automatic Calibration





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Final Actuation System

- Rack and Pinion System
  - Simultaneous Turning for Various Louver Sizes
  - Simple, Reliable, Versatile

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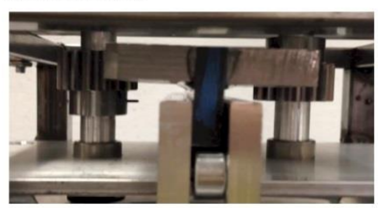
Rack and Pinion



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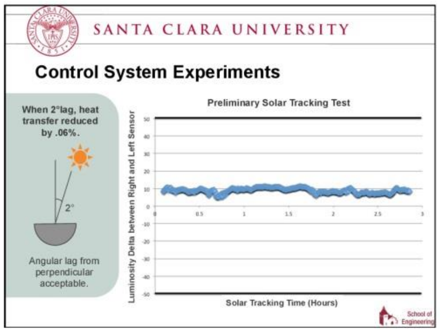
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Control System Experiments
When 2°lag, heat transfer reduced by .06%.
2°
Angular lag from perpendicular acceptable.
Preliminary Solar Tracking Test
Luminosity Delta between Right and Left Sensor
Solar Tracking Time (Hours)
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Experimentation
Hutch Testing Environment
Control and Experiment Insulated Stationary Rooms
Measure Temperature, Luminosity, and Energy Consumption
Optimize Hutch Location
Single Louver Prototype
Quarter-Cut versus Half-Cut
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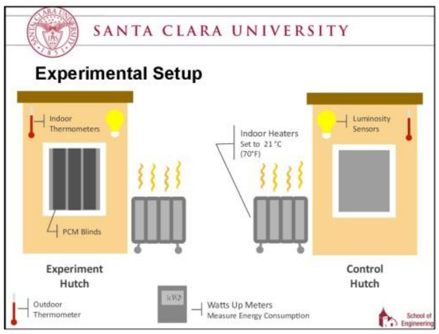
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Experimental Setup
Indoor Thermometers
PCM Blinds
Indoor Heaters Set to 21 °C (70°F)
Luminosity Sensors
Experiment Hutch
Control Hutch
Outdoor Thermometer
Watts Up Meters Measure Energy Consumption
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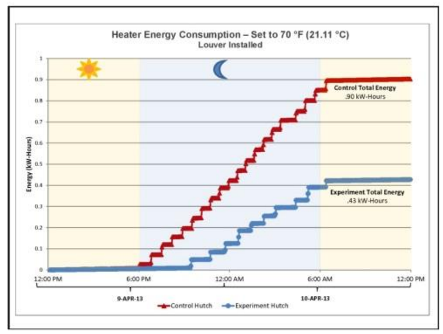
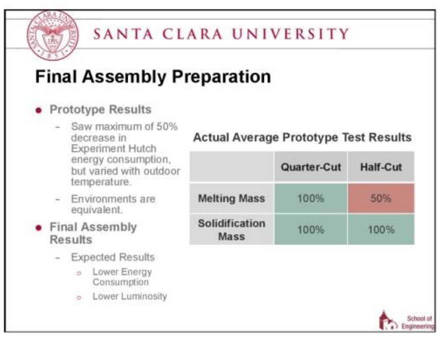

Heater Energy Consumption – Set to 70 °F (21.11 °C)
Louver Installed
Energy (kW-Hours)
Control Total Energy .90 kW-Hours
Experiment Total Energy .43 kW-Hours
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
9-APR-13
10-APR-13
Control Hutch
Experiment Hutch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Final Assembly Preparation
Prototype Results
Saw maximum of 50% decrease in Experiment Hutch energy consumption, but varied with outdoor temperature.
Environments are equivalent.
Final Assembly Results
Expected Results
Lower Energy Consumption
Lower Luminosity
Actual Average Prototype Test Results
Quarter-Cut | Half-Cut
Melting Mass | 100% | 50%
Solidification Mass | 100% | 100%
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Customer Needs
Health & Safety
Non-Toxic Paraffin Wax. Grounded system to prevent electrical shock.
Price & Cost
$1375.58 more savings with PCM Blind in comparison to saving in the bank for 10 years.
Aesthetics
Design stow-away feature. Future sleek design to minimize bulkiness.
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4

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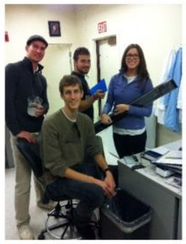
Summary

- **Accomplishments**
  - Design and Analysis of Subsystem Iterations
    - Louvers
    - PCM
    - Control System
  - Experiment Set-Up Preparation and Optimization
- **Future Objectives**
  - Final System Assembly + Testing
  - Integration into Kennedy Commons
  - Mass Production Business Plan



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Acknowledgements

A thank you to the **Lawrence Berkeley National Laboratory**, **Willem and Maria Roelandts** for the Santa Clara University **Center for Science, Technology, and Society**, and **Santa Clara University School of Engineering** for their funding and contributions.

We would also like to thank **Dr. Hohyun Lee**, **Laughlin Barker**, **Aitor Zabalegui**, and **Dr. Timothy Hight** for providing their knowledgeable aid in the project.

Also, a big thank you to **Donald MacCubbin**, **Mike Sizemore**, and **Bersabe Morales** for their aid in the manufacturing process.

Thank you for listening.

Questions?

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Chapter A.8: Invention Disclosure Form

Santa Clara University

Invention Disclosure Form

Office of Research Initiatives
Santa Clara University
500 El Camino Real
Santa Clara, CA 95053
(408) 551-1817 phone
(408) 551-1873 fax

Santa Clara University is committed to supporting the development of new technologies. *Faculty Handbook* section 3.7.5 describes the University policy on patents including the distribution of royalties. The patent policy of the University applies to all potentially patentable discoveries or inventions conceived or first reduced to practice by anyone using University funds, material, or facilities. In particular, the University patent policy is defined in terms of three categories of inventions:

Category 1. *Discoveries or inventions that are subject to the terms of sponsored project or other agreements between the University and a third party.* These inventions shall be disposed of in accordance with the terms of the applicable agreement. Most agreements provide that the University will take title to inventions and will grant certain license rights to the sponsor.

Category 2. *Discoveries or inventions that involve the significant use of funds, materials, or facilities administered by the University but that do not involve University obligations to a third party.* These inventions shall be the property of the University. Significant use occurs when the University provides resources above and beyond those that would be routinely available to the inventor as a direct result of his or her affiliation with the University.

Category 3. *Discoveries or inventions that do not involve either University obligations to third party or the significant use of funds, materials, or facilities administered by the University.* These inventions shall be the property of the inventor.

Furthermore, under the University patent policy, any discovery or invention conceived or first reduced to practice by anyone using University funds, material, or facilities must be disclosed promptly to the University by means of this Disclosure Form except for discoveries or inventions in which the inventor has sole ownership rights. The University has contracted with the Stanford Office of Technology Licensing to evaluate disclosures and manage patent procedures for inventions that shall be the property of the University. The patent process is coordinated by the Associate Provost for Research Initiatives and involves the following steps:

1. Complete this disclosure form.
2. Submit the completed, signed hard copy of the form to the Associate Provost for Research Initiatives.
3. Upon receipt, the Associate Provost will contact the Stanford Office of Technology Licensing to formally initiate the disclosure evaluation process.

4. The inventor can expect to be contacted by a representative of the Stanford Office of Technology Licensing to evaluate the disclosure and start the process of determining if the inventions meet the criteria for pursuing a patent.
5. Any questions regarding the process should be directed to the Associate Provost for Research Initiatives (ashachter@scu.edu).

An invention and technology disclosure is a legally important document that describes what is invented and the circumstances under which the invention was made or the technology created. Please complete the disclosure form carefully.

1. Title of the invention or technology

Automated Bi-Directional Solar Thermal PCM Blind System

2. Description of the invention or technology

2a. General purpose of the invention and what problem it solves.

The average California resident uses approximately 21,000 combined kilowatt-hours of electricity and natural gas each year, equating to a $900 annual utility bill[10]. Natural gas and coal resources continue to deplete, while the amount of energy consumed by Americans continues to increase. Today, there is a continuous effort to create energy efficient appliances, to aid in daily reduction of energy consumption. In particular, HVAC (heating, ventilation and air conditioning) systems account for 30% to 40% of the energy consumed in an average residence throughout the United States[11]. Eliminating the need for heating and air conditioning would decrease utility costs and preserve natural resources.

Rather than inventing a more efficient HVAC system, our invention focuses on reduction of the cooling and heating loads in order to reduce the energy consumption for an HVAC system. The invention will absorb and store solar heat energy during the day, while keeping a building cool, and emit heat energy at night when the temperature drops. The average California resident cools their home during the day and heats it at night, to varying degrees dependent on the season. Hence, the utilization of the proposed design that combines those benefits would be optimum for areas with the same weather characteristics. This concept will be integrated into a blind system, so that a common household item will have reduced cooling and heating cost without significant installation costs.

[10] "Efficiency Partnership." Flex Your Power. www.fypower.org/pdf/challenge_cheatsheet0806.pdf (accessed November 19, 2012).
[11] "Flex Your Power - Residential Product Guides." Flex Your Power - California Energy Efficiency and Conservation. http://www.fypower.org/res/tools/products_results.html?id=100143 (accessed November 19, 2012).

2b. Technical description of the invention including a discussion of features believed to be new and advantages over existing methods, devices or materials, and a description of unique and non-obvious aspects of the invention. For software, describe any novel algorithms. For a database, describe novel features of the structure. Attach photos, drawings or other technical data/material as appropriate.

(Already mentioned the purpose in the previous section. Let's focus on the technical description in this section.) The invention encompasses a set of window blinds filled with a phase change material (PCM), which stores the sun's energy and releases the stored energy to the inside at night. Room temperature is also kept cool during daytime since the proposed design blocks incoming solar energy. A ***thermally absorptive facing of the blind is automatically controlled*** to track the sun throughout the day ***with a unique actuation system***. Historical weather data for the same location, time, and season is used to trigger the actuation system and rotate the blind system, so that it tracks the sun and maintains perpendicularity to the sun's rays and is based on the known movement of the sun.

Invention's Unique Features:

1. Thermally absorptive edge controlled to face sun with actuation system.
2. Phase change material inside optimized crescent- shaped louver.
3. Highly emissive blackbody louver face to effectively absorb and emit heat.
4. Elliptic reflective and thermally insulating louver back to act as radiation shielf to room during the day.

In comparison to current technology and patents, this invention differs with the ***incorporation of Phase Change Materials inside of louvers*** within an overall blind system. As shown in the 'Patent and Project Search' attachment, majority of devices invented store Phase Change Material in tanks or between glass windowpanes. The contrary to these patents and current technology are inventions that improve blind systems. Our invention seeks to reduce heating and cooling loads by shading and emitting heat energy at optimum times of the day, whereas current blind technology on the market and patents seeks to provide a thermal barrier and change window characteristics similar a wall in order to keep light and cooling or heat energy out of a room. A comparison of each patent is provided with the attachment.

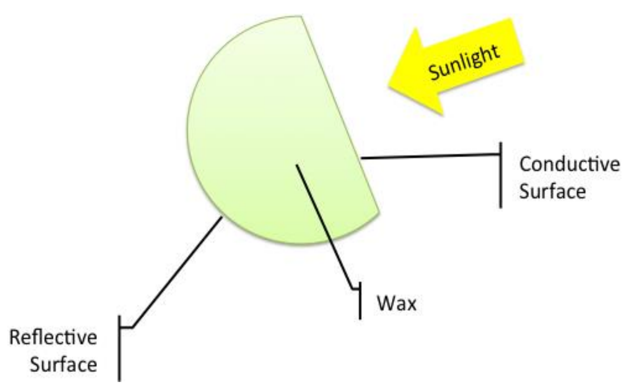

Figure 1: A single louver prototype cross-section, functioning during the day.

The invention will improve and add benefits to a common household item, while eliminating the need for another. The concept not only combines a blind with a heating system, but also optimizes each component so that it is as efficient as possible. The invention consists of ***crescent-shaped louvers*** to replace traditional window blind or shading systems. The window shading system will be installed indoors, in front of a window. A cross-section of the basic louver prototype is shown in Figure 1. One unique optimization component was the decision for each material used for each individual component within the design. To optimize PCM melting, ***the flat side of the louver has a highly emissive material to effectively absorb and release solar energy***. A graphite-coated acrylic is exploited to realize black body, or material that will ideally absorb all incoming solar radiation. ***The crescent back-edge of the louver is comprised of a reflective and insulating surface to avoid heat loss***.

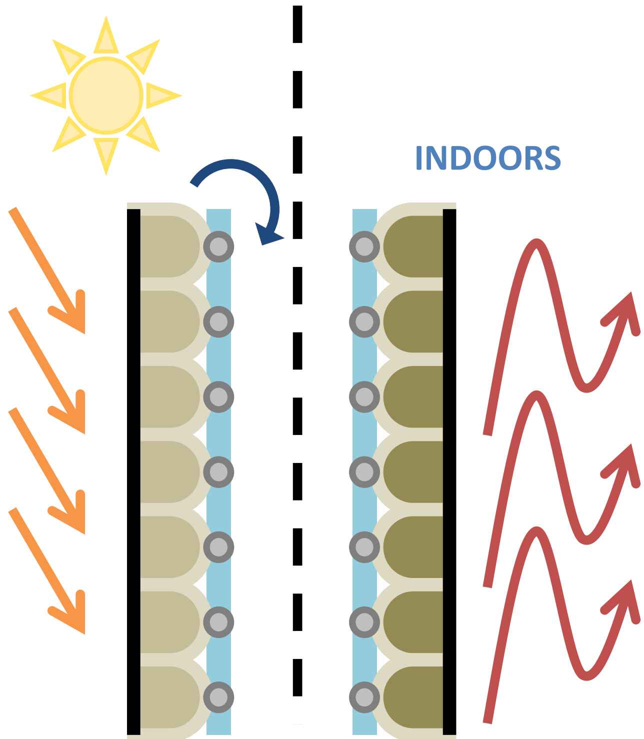

Figure 3: Top view of the rotating louvers with heat absorption during the day and emission at night, in order to replace nighttime space heating.

The louvers holding the PCM are made of half a ***4" Thermoplastic Acrylonitrile-Butadiene-Styrene (ABS) standard pipe, with a 1/8" acrylic plate adhered in a watertight manner to its face and 1/8" ABS half circles adhered to each end to fully waterproof the louver***. ***The back wall of the louver is coated with an aluminum coat to form a radiation shield to prevent unnecessary heat transfer into interior spaces during the day***. ABS was chosen for its thermal characteristics, high availability and ease of manufacture. The thermal conductivity of ABS is approximately 0.25 $W{\cdot}m^{-1}{\cdot}K^{-1}$ [12] that provides an optimum thermal barrier when combined with the metallic inner core. For comparison, copper is a highly conductive material with a thermal conductivity of 401 $W{\cdot}m^{-1}{\cdot}K^{-1}$ [13] and would be the worst thermal barrier, whereas fiberglass has a thermal conductivity of 0.04 $W{\cdot}m^{-1}{\cdot}K^{-1}$ [4] a good insulator. ABS has thermal characteristics closer to fiberglass and is therefore optimum for our invention. The current crescent louver design size was optimized so that each blind has a large surface area to absorb radiative heat and high volume to store large quantities of PCM. The louvers must work effectively, be aesthetically pleasing, while maintaining a low manufacturing cost. The attached PVC Optimization Calculations and Excel sheet show analysis of available energy for varying crescent shapes. Obviously, the largest diameter PVC produced the highest available energy, but that also increases the depth and decreases the surface area to volume ratio, which should be as large as possibly so that the PCM will melt completely during daytime. The current design is for a half or quarter cut 4-Inch ABS which both theoretically produce 2.44 kWh and 1.19 kWh of energy with a PCM mass to surface area ratio of 8.20 kg/m^3 and 5.26 kg/m^3 because of their combined benefits for optimum PCM phase change.

In order to absorb the largest amount of heat energy, our design has ***a unique tracking mechanism*** incorporated so that the Phase Change Material will be facing in the direction of the sun at all times, and therefore improving the heat absorption process and minimize energy consumption for the actuator. The control system will operate the blinds so that they switch position throughout the day, depending on the temperature, and brightness of the sun. Temperature, brightness, and motion sensors will be used to detect any significant drop in the ambient temperature and light, in which case the louvers will automatically flip inward, thus beginning the solidification of the wax and the heating of the house. The

[12] SubsTech. "Thermoplastic Acrylonitrile-Butadiene-Styrene (ABS) [SubsTech]." Substances and Technologies. http://www.substech.com/dokuwiki/doku.php?id=thermoplastic_acrylonitrile-butadiene-styrene_abs (accessed February 7, 2013).
[13] Georgia State University. "Thermal Conductivity." HyperPhysics: Department of Physics and Astronomy. hyperphysics.phy-astr.gsu.edu/hbase/tables/thrcn.html (accessed February 6, 2013).

three sensors will be programmed to work together to ensure that the available thermal energy is used to space heat the house in the most efficient manner. The base provides support for the louvers and a way to actuate them in a manner that allows at least 180 degrees of rotation in order to follow the sun during the day and then turn in to face the interior spaces at night.

2c. Possible variations and modifications to the invention as well as products or processes that could results from the invention.

(This section describes how this invention can be applied or modified, and prevents others from using this technology by small modification.)

Possible variations and modifications to this invention would be any improvements or further optimizations of the current design, or utilization of the same concept of combining heating and cooling benefits into an alternate product. Improvements or optimization may be to the current materials, design, and components chosen for the face, reflective back, assembly, Phase Change Material, and control system. Potential variations or modifications may include: a wall, door, garage, skylight cover, pool cover, or any other device that is accessible to outdoor solar energy and the indoors of a building. All of the potential variations or modifications could be filled with a Phase Change Material and integrated with a solar tracker control system that also absorbs solar energy during the day and flips inwards to emit heat at night. Each product also provides the benefit of shading and keeping the indoors cool during the day.

The current actuation system prototype utilizes historical weather data and a low torque stepper motor that adjusts the azimuthal angle of the single louver prototype to input angles. The current code is dependent on input angles that are desired based on a time of day and the location of the louver on the globe, but will potentially utilize solar panels to track the actual current sun movement. Once the construction/welding of the system that holds the louvers in place is completed, the true stepper for the project (which supplies more torque and up to 3 Amps of current) will be utilized. Our current step involves determining/implementing the best way to actuate the louvers with the stepper motor. Once this step is complete, our first true size prototype will be complete.

Our current louver design has been selected to optimize the volume to surface area ratio of the individual louvers while maintaining a high PCM volume to provide the required latent heat. Currently, two louver designs are being tested: a 4-inch ABS pipe is cut lengthwise in half and quarter length sections. In other words, one louver design has a 4-inch diameter and is a strict semicircle, while the other design has a 2-inch diameter and is more of a crescent shape. Both will be potentially tested for the final design with multiple louvers. The difference between the two designs is based around the time it takes for the wax to change its phase. The dimensions that are being altered in this test are the cross-sectional area of the louver (affecting the amount of solar heat-flux that hits the wax) and the mass of wax per louver (affecting the melt/solidification time). The addition of radiation shielding and improvements in production methods have allowed us to improve other thermal characteristics of the louvers, while allowing for easy assembly within the greater context of the controls system and supporting frame. Our louver could potentially change in size or material depending on how our current prototype performs in testing.

2d. Competing technologies including current solutions for the same problem, how and how much better the invention is relative to competing technologies, listing of related technical papers or patents for similar technology, a description of degree of research in the field:

The two major types of commercially released products on the market that shade and heat a home are window coverings and HVAC (Heating Ventilation and Air Conditioning) systems. Our invention differs in that it combines the heating and cooling benefits of both of these devices into one device. As shown in the 'Patent and Project Search' attachment, majority of devices invented store Phase Change Material in tanks or between glass windowpanes. The contrary to these patents and current technology are inventions that improve blind systems. Our invention seeks to reduce heating and cooling loads by shading and emitting heat energy at optimum times of the day, whereas current blind technology on the market and patents seeks to provide a thermal barrier and change window characteristics similar a wall in order to keep light and cooling or heat energy out of a room. A comparison of each patent is provided with the attachment.

In order to design a blind system that appeals to customer needs, similar products were analyzed as potential competitors. The strengths and weaknesses of each were taken into consideration to determine which features are most important to incorporate in our design. Most importantly, we examined the thermal characteristics of each product by comparing insulating resistances, referred to as R-Values. A low R-value results in significant heat loss, whereas a high R-value has less heat loss. Each window and blind system is summarized in Table 1. As shown, a standard set-up with a single-pane window and typical linen pleat blind is the most inexpensive option, but also the least insulative, increasing utility costs. Cellular shades are the most similar product on the market to our proposed design with a high thermal resistance, but are extremely expensive and do not emit heat energy.

Our proposed design will have an insulated crescent back, and when combined with a double-pane window will have an expected R-value of 7.8. Though this is fairly high, if we need an even more insulation silica aerogel will be added to increase the R-value to 6.8. Based on calculations, our blind system will emit 2.526 kWh of heat energy for a 3-foot by 7-foot window, a feature that none of the other blind systems have. If our device works as expected and we are able to keep the cost and price of our system below $800, while taking aesthetics into consideration, we could potentially have the best product on the market.

Tests were performed on two distinct Phase Change Materials. These PCMs mostly encompass an average paraffin wax, with slight modifications to alter various thermal properties. Other benefits of these waxes also include that they are noncorrosive, non-toxic, and inexpensive materials. An energy analysis was performed on both PCMs, to determine how long it will take for each wax to change phase (solid to liquid, and liquid to solid). By determining an optimal melting time of about five hours and an optimal solidification time of nine hours, the ideal theoretical mass of wax in each louver was calculated to be 7.75 kg. The wax that was chosen has a melting temperature of 28°C, and has a latent heat of fusion of 245 kJ/kg. This chosen wax could potentially change to a different Phase Change Material, or alternate thermal storage material or mechanism in the future.

To date, TES (thermal energy storage) technologies have primarily been developed to use PCMs either as simple thermal mass or in complicated systems in which the PCM is pumped through the structure. In each case, the final result has suffered from an excessive ambient heat loss, or required an unrealistic amount of pumping power. Our invention eliminates or optimizes these failing characteristics to effectively utilize Phase Change Materials.

Patent and Project Search

Suppressing heat flux in insulating glass structures
Patent Number: EP 1390598 A1
Abstract: Inner (32) and outer (34) juxtaposed glazed panes are separated from each other by an interlayer containing a gas, and the gap between the panes is closed by a seal (48) near the perimeter of the panes. A thermally conductive, hermetically sealed receptacle (36) is positioned between the panes. The receptacle contains a phase change material (38) that reversibly absorbs, stores, and releases heat in response to temperature changes at least at one of the glazed panes.

http://www.google.com/patents/EP1390598A1?cl=en&dq=phase+change+material+blinds&hl=en&sa=X&ei=scYOUeO-LsL2igLI54HoBw&ved=0CDYQ6AEwAQ

Comparison: This patent focuses on improvement of an actual window using Phase Change Material, whereas our patent focuses on the improvement of a blind system, to increase the benefits of a window accessory beyond its current use.

Energy-Efficient Smart Window System
Patent Number: US 20120307352 A1
Abstract: Energy-efficient windows incorporating spectrally selective optical elements capable of providing desirable optical characteristics (transmission, reflection, refraction or diffraction) for different wavelengths are disclosed herein. More specifically, energy-efficient windows incorporating suitably designed diffraction gratings to optimize the efficiency of the utilization of different spectral components of the solar radiation are disclosed.

http://www.google.com/patents/US20120307352?dq=phase+change+material+blinds&hl=en&sa=X&ei=scYOUeO-LsL2igLI54HoBw&ved=0CE4Q6AEwCQ

Comparison: This patent focuses on improvement of an actual window system and does not incorporate Phase Change Material. This patent examines the optical characteristic and heat transfer's affect on an actual window, rather than a blind system.

Modular passive solar energy heating unit employing phase change heat storage material which is clearly transparent when in its high-stored-energy liquid state
Patent number: 4532917
57 ABSTRACT A highly effective modular passive solar energy heating unit for heating an enclosed space employs phase change heat storage material which is optically transparent to visible light when in high stored energy liquid state enabling a viewer to see through clearly and which is translucent milky white when in low stored energy solid state for providing pleasant illumination to the enclosed space when first illuminated by sunlight in the morning This phase change material in a sealed container having two opposite surface areas transparent to sunlight is polyethylene glycol having a heat of fusion of about 33 to 37 cal gm 4,170 to 4,670 Btu's per cubic ft a melting point of about 13 to 25 C 55 F to 77 F a specific gravity of about 1,125 at 20 C and desirable isotropic freezing and melting characteristics with only very modest volume change during phase change A dye soluble therein may be included for increasing solar energy absorptivity when translucent and for decreasing glare and direct penetration of sunlight into the space when transparent The unit additionally contains at least one clearly optically transparent glazing layer facing the sunlight preferably including an insulation layer to transmit short wavelength solar

radiation while blocking longer heat rays for retaining thermal energy within the enclosed space In preferred embodiments there are two layers of closely spaced parallel transparent glazing near the sealed container these layers being between incident solar radiation and the container.

Comparison: This patent utilizes Phase Change Material within a heating container; it utilizes sunlight to create a heating unit. This patent does not incorporate their heating unit with a Window or Blind system.

Building Energy System

Patent Number: US 20120318475 A1

ABSTRACT: There is disclosed a building energy system comprising a building enclosure having an insulated building envelope that incorporates at least one perimeter fenestration assembly, and an integrated mechanical system that provides heating and cooling. The integrated mechanical system comprises a cold thermal storage tank, a hot thermal storage tank, and a heat pump that transfers heat from the cold thermal storage tank to the hot thermal storage tank. The building enclosure also comprises an air stratified ventilation system comprising at least one upper exhaust outlet and at least one lower supply intake. The upper exhaust outlet incorporates a heat exchanger that recovers heat from outgoing air. The heat exchanger is connected to the cold thermal storage tank. Energy performance of the at least one fenestration assembly may vary or be automatically controlled such that the heating and cooling loads of the integrated mechanical system are at least partially balanced.

Comparison: This patent utilizes heat transfer concept and tools to provide heating and cooling inside a container, essentially an HVAC system within a storage tank. It uses similar heating concepts to our patent but does not incorporate their heating unit with a Window or Blind system.

Thermal insulation curtain for windows, doors and the like

Patent Number: EP 0083595 B1

ABSTRACT (text from WO1983000280A1)

The thermal insulation device for windows, doors and the like is provided as a curtain (10) or a roller blind. As a carrier element, it comprises a synthetic sheet covered with at least one metal layer deposited by vaporization or spraying and having a high reflection power for large wavelength thermal radiation. The synthetic sheet is divided at least locally for example by means of perforations (11) or by addition of narrow strips (15, 16) with a view to modify its mechanical characteristics to decrease the elasticity. The structure thus obtained, which may be used as curtains or roller blinds, is aesthetic and constitutes an important improvement.

Comparison: This patent is for a blind system that affects the temperature of a room but with the use of different materials. This patent seeks to insulate a room, whereas ours seeks to heat a room. This patent does not include Phase Change Material but uses similar heat transfer concepts.

Thermal shade

Patent number: 4574861

Abstract: A thermal shade for limiting the amount of thermal energy which enters a structure through an opening therein is disclosed. The shade comprises a plurality of integrally formed elongated closed rectangular tubes which have a dead air space, are arranged in parallel relation to each other, and are connected on the side opposite the opening by living hinges. The shade also includes means for positioning shade to limit the thermal energy entering the opening.

Comparison: This patent is for a blind system that seeks to insulate a room and hinder the thermal energy from entering. It utilizes similar tubes used in our patent louver design, but they are filled with air rather than Phase Change Material. Our patent seeks to heat a room, whereas this one seeks to provide an insualtive barrier.

Venetian blinds with magnetic controller for regulation

Patent Number: EP 2271813 B1

ABSTRACT (text from WO2009122222A1)

The core of the invention is that the space between the windowpanes could be completely sealed from the environment, after the Venetian blinds regulated by magnets have been installed. Magnets are placed between window panes in the freely rotating bearing hollow pipe and in the bottom bearing rail together with the related strings, that is ladder which hold the individual slats or strips of the Venetian blind. After installing the inner part of the Venetian blind, the space between the windowpanes is permanently sealed from the environment. Such insulation glass is placed in a window or door. All that is necessary for using and regulating the Venetian blinds are the bottom and top external rail, which enable the Venetian blind to be: rotated around the longitudinal axis for 180°, lifted and lowered by the external bottom batten, and lifted and lowered by the top external batten or moved diagonally. The invention consists of strings which form ladder (11), which hold the horizontally fitted slats (12) at the appropriate distance. This structure hangs on the freely rotating bearing hollow pipe (4), and at the bottom it is connected to the inner bottom section (7). Each magnet (8b) in the bearings (8) or the inner top/bottom contact magnets (8a; 18 a) are fitted to be in the opposite magnet pole in relation to the poles of the external top/bottom contact magnets (18; 18b) on the external top and bottom regulating batten (5; 6) Magnets which glide horizontally along the external top regulating batten (5) attract magnets fitted at the edges of the freely rotating bearing hollow pipe (4). The rotation controller (23a; 23b) enables rotation of the slats (12) for 180°. By moving the bottom/top external regulating batten (6; 5) together with the related magnets it is possible to move the Venetian blind up or down, including moving of only one side of the top/bottom regulating batten (5; 6). Therefore, interaction of the mentioned elements of the invention it is possible to shade any part of the window, including shading diagonally along the window, which will be described in detail later.

Comparison: This patent is for a blind and window system that also seeks to seal the room from the environment to provide an insulative barrier. It rotates to shade from the sun, similar to the concept of our control system, but with the use of magnets whereas ours uses an electrical system and seeks to follow the sun for shade and absorption of solar energy.

Table 1: Benchmark for Comparison of Blind and Window Systems

Product[14]	Cost of Blind System (3' x 7')	Heat Loss (R-Value[15])	Comparison
 Single-Pane Window + Standard Linen Pleat Blinds	$200	Maximum Heat Loss (3.2)	Provides very little insulation, and no heat production. Most inexpensive, but least effective.
 Double-Pane Window + Wood Blinds	$350	Median Heat Loss (4.0)	Provides more insulation, but no heat production. More expensive, with moderate effectiveness.
 Double-Pane Window + Cellular Motorized Shades	$850[16]	Minimum Heat Loss (6.6)	Retracts up and down with remote, and the cellular material prevents light and heat transfer from filtering through when closed. Good insulation, but no heat production and expensive.
Phase Change Material in Automated Window Shades	<$800	Heat Source (7.8 or 9.8)[17]	Provides the best insulation and emits 2.526 kWh of heat energy for a 3' x 7' window. Includes a potentially less expensive motorized control system.

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[14] "Custom Window Treatments - Modern Drapes, Window Shades, Fabric Blinds, Silk Drapery & Contemporary Curtains | The Shade Store." Custom Window Treatments - Modern Drapes, Window Shades, Fabric Blinds, Silk Drapery & Contemporary Curtains | The Shade Store. http://www.theshadestore.com/ (accessed November 10, 2012).

[15] "Next Day Blinds: Energy Efficient Window Treatments." Next Day Blinds | Shades, Blinds, & Shutters. http://www.nextdayblinds.com/energysavers.asp (accessed November 19, 2012).

[16] "Menards - 500." Menards - Dedicated to Service & Quality™. http://www.menards.com/main/skusummary.html?cid=9239&sid=1857595&pid=1857536 (accessed November 10, 2012).

[17] "Cold Climate Energy Efficiency Guide for Window Coverings." Discount Blinds & Shades | BlindSaver.com. http://www.blindsaver.com/designdoctor/coldclimate.jspx (accessed November 19, 2012).

2e. Stage of development including current state of research and steps to commercialization:

Our team is currently in the development stage and has made a variety of louver prototypes and a single completed assembly prototype with a single louver. We are currently in the development of completing a final blind system with a full set of louvers for a 3-foot by 7-foot window for the Santa Clara University Design Conference and 2013 Solar Decathlon house. We have conducted a customer needs assessment (attached) in order to determine what features need to be incorporated in order to have an appealing commercially released product. The main concerns were in regards to aesthetics, maintenance, and safety, which are being taken into consideration and improved with each prototype.

2f. Commercialization possibilities:

This product could potentially be used in any residential and commercial building with optimization and design for various sizes. Blind and HVAC systems are now a necessity in the majority of buildings throughout the world, and this product will reduce energy consumption. There are potential improvements to reduce cost and increase safety of the device due to the actuation system. In addition, each component involved within the design has a shelf life of greater than 20 years, so the product would have a high return on investment.

Our invention could also be a potential simple solution to the hot days and extremely cold nights of Northern Africa that does not require infrastructure or education to understand and operate. By simply providing the citizens of the Northern African region with a technology that absorbs the sun's daytime energy and, with the pull of a simple switch, turns to release that energy at night, we hope to provide improved comfort and health to under-served populations.

3. **Inventors or developers** (provide the following for all presumed inventors or developers; use an additional disclosure form if there are more than three inventors)

Total number of inventors: 5

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Home Phone: N/A
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Citizenship: United States Citizen

4. Obligations to third parties (attach any inventions sections of third party agreements)
4a. What funds supported the work leading to this invention? Please list all sources of funding for the invention (include any federal, non-federal, foundation, and industry funding, gifts, Santa Clara University funds, etc.). For non-SCU funds include: contract/grant number, sponsor, and PI(s).

Sponsor	Dept ID	Program	Project/Grant Number	Class	PI
Center for Science, Technology, and Society	MECH	RSCH	12ROEL03		
Lawrence Berkeley National Laboratory	MECH	RSCH	LBNL04		Hohyun Lee
Santa Clara University School of Engineering	ENGSCL	ENGSP	IN	FAC18	

4b. Are you a party to any other agreement(s) pertaining to the invention (e.g. material transfer agreement, collaboration, patent agreement with any other entity)?

☑ yes ☐ no

If yes, please list third party names and types of agreements:

See listed sponsors above.

5. History of invention or technology

5a. Date of initial idea: June 2012

The invention began as a student Senior project with an initial concept provided by the Faculty Advisor. Dr. Lee has a background in Thermal Systems and developing ideas that involve Phase Change Materials. The concept was to incorporate a Phase Change Material (PCM) within a residential and commerical item that is not typically used as a heat source, in order to create an invention that combines two benefits or more into one product. The Phase Change Material would provide storage of heat energy without electric or gas consumption and increase the HVAC system's efficiency in a building structure. The item chosen to combine with the PCM would provide the invention with its overall benefit. It was then determined that the item chosen would have to be accessible to a heat source, preferably renewable to decrease energy costs and consumption, so that the Phase Change Material could absorb heat energy for storage. It was also determined that this item would require volume to hold enough Phase Change Material to absorb, store, and emit enough heat into a building. In any bulding that would require heat, residential or commercial, windows were the closest widely purchased item to the sun, a renewable energy source. Since one purpose of a window is to be transparent, while providing thermal insulation, filling a window with a PCM was not an option because it would cover a window. The team then established that the next widely purchased item for a window was a blind system, which has a standard purpose to provide shade or privacy to the inside of the building. So, the initial idea to combine Phase Change Material with a blind system since it is purchased to provide shade and cover a window, and adding a thermal storage aspect would only benefit the initial product.

5b. Date of conception (when all the essential elements of an invention were formed in the inventor's mind): August 2012

After the initial concept was developed the student team and advisor began establishing all the required components of the system and designing each element. It was decided that a hollow set of louvers would be developed, with an optimized shape to increase the surface area to PCM volume ratio. It was decided that a control system and assembly would be designed and built to rotate the louvers towards the angle of the sun to absorb the solar energy, and then flip inward at night to emit the stored energy to the room. The initial intention was to write tracking code that inputted preset angles based on historical weather data of the sun's location and sunset at various times of the year in the testing location. After this was completed, development of a control system that follows the sun and then (at detection of low luminosity late in the afternoon) the louver system would perform a 180° turn and heat energy would be emitted into the building.

5c. Date first reduced to practice (first successful demonstration of the invention):

The first working prototype for the invention that incorporated all components: Single Louver, Actuation System, Tracking Code, Phase Change Material, and assembly manufacture was completed on January 28, 2013. A picture of this prototype is attached and shown inside one of two hutches that will be used for experimentation. One hutch will be used as a controlled environment, since both hutches were built with insulation and double-pane windows.

5d. Date and venue of first public disclosure (date and venue of proposal or manuscript submission, date and venue of conference presentation, date and venue of electronic or web postings):

A proposal was sent to the Lawrence Berkeley National Laboratory (LBNL) in July 2012 to be an investor in our initial idea, and was accepted in September 2012.

A proposal was sent to the Santa Clara University Center for Science, Technology and Society in October 2012 to be an investor in our initial idea, and was accepted in November 2012.

A proposal was sent to the Santa Clara University School of Engineering in October 2012 to be an investor in our initial idea, and was accepted in November 2012.

An oral proposal was presented for the Senior Design course to Santa Clara University Senior Mechanical Engineering students and selected judges at the start and end of the Fall Quarter, September and December 2012.

The Lawrence Berkeley National Laboratory will reveal the teams chosen for the Max Tech and Beyond: Ultra-Low Energy Use Appliance Design Competition on February 15, which includes a description and photos of our current invention, prototype design.

5e. Date and venue of any future public disclosures (date and venue of future, planned publications, conference presentations, etc.):

February 15, 2013 – LBNL Website Reveal
April 13, 2013 – SCU Preview Days 1
April 14, 2013 – SCU Preview Days 2
May 9, 2013 – SCU 43rd Annual Senior Design Conference
May 23, 2013 – LBNL Webinar Presentation
July 26, 2013 - Final Team Report Due

6. **Rights and royalties (*all* inventors must sign; please use another disclosure form for more than three inventors)**

I agree that all rights and royalties will be distributed per Santa Clara University's current patent policy as stated in the Faculty Handbook section 3.7.5. The categories of inventions defined in the Faculty Handbook are also described on page 1 of this disclosure form. I understand that the University will determine the invention category based on any third party agreements and/or the use of funds, materials or facilities administered by the University related to the invention disclosed herein.

Inventor's name (print or type): Hohyun Lee

____

Inventor's signature Date

Inventor's name (print or type): Ali Nash

____

Inventor's signature Date

Inventor's name (print or type): Jake Gallau

____

Inventor's signature Date

6. **Rights and royalties (*__all__* inventors must sign; please use another disclosure form for more than three inventors)**

I agree that all rights and royalties will be distributed per Santa Clara University's current patent policy as stated in the Faculty Handbook section 3.7.5. The categories of inventions defined in the Faculty Handbook are also described on page 1 of this disclosure form. I understand that the University will determine the invention category based on any third party agreements and/or the use of funds, materials or facilities administered by the University related to the invention disclosed herein.

Inventor's name (print or type): Alex Zatopa

____

Inventor's signature Date

Inventor's name (print or type): Quinlan Adler

____

Inventor's signature Date

Inventor's name (print or type):

____

Inventor's signature Date

7. Received by (to be completed by Office of Research Initiatives):

Form complete: yes no

____

Signature **Date** **Time**

If form in incomplete, what information is needed?

Date form is completed:

____

Signature **Date** **Time**

Please submit a hard copy of the completed disclosure to:
Office of Research Initiatives
St. Joseph's Hall
Santa Clara University
500 El Camino Real
Santa Clara, CA 95053

Attachments

Photographs

- See attachments for earlier development photos and CAD models and drawings. The photos shown below are for our current prototype and the CAD models and drawings included are for the potential final blind system that incorporates a full set of louvers to cover a 3-foot by 7-foot window.


ENERGY STAR

Chapter A.9: Parts List Spreadsheet

Version 04 06/02/13

Subsystem	Component Description	Part #	Revision	Quantity	UOM	B/M/O [1]	Vendor [3]	Vendor P/N	Cost/Part	Cost	Reponsible Person	Man-Hours [2]	Design	Procurement	Build (EA)	Assembly	Order or Start Date	Receive or Finish Date
Control System																		
	Arduino Uno – R3	00001	N/A	1	EA	B	SparkFun	DEV-11021	$29.95	$29.95	Alex	0	0	0	0		5-Oct-2012	9-May-2013
	Servo Motor	00002	N/A	1	EA	B	Servocity	HS-5685HB (7:1 ratio)	$129.98	$129.98	Alex	0	0	0	0		5-Oct-2012	9-May-2013
	Power Cord	00003	N/A	1	EA	B	Digi-Key	839-1184-ND	$2.60	$2.60	Alex	0	0	0	0		5-Oct-2012	9-May-2013
	AC 110/220V DC 5V 10A 50W Switching Power Supply Driver	00004	N/A	1	EA	B	Factory Monster	a10073000ux0080	$21.53	$21.53	Alex	0	0	0	0		5-Oct-2012	9-May-2013
	Hook-up Wire – Black	00007	N/A	1	EA	B	SparkFun	PRT-08022	$2.50	$2.50	Alex	0	0	0	0		5-Oct-2012	9-May-2013
	Solder Leaded – 100-gram Spool	00008	N/A	1	EA	B	SparkFun	TOL-09161	$5.95	$5.95	Alex	0	0	0	0		5-Oct-2012	9-May-2013
	ProtoBoard – Round 2"	00010	N/A	1	EA	B	SparkFun	PRT-08810	$2.95	$2.95	Alex	0	0	0	0		14-Jan-2013	9-May-2013
	↦ Control System Assembly	M0001	N/A	1	EA	M					Alex	25	15	0	0	10	25-Nov-2012	24-May-2013
	Subsystem Total									**$195.46**		**25**						
Louver Assembly																		
	ABS (Acrylonitrile Butadiene Styrene) 4-Inch x 7-Foot Cut Back	00011-01	02	7	EA	M	Home Depot	N/A	$7.64	$53.46	Jake	4.5	1	0	0.5		23-Sept-2012	6-Mar-2013
	4-Inch x 7-Foot Acrylic Face	00012-01	02	7	EA	O	Tap Plastics	Custom	$2.63	$18.41	Jake	1	1	0	0		23-Sept-2012	6-Mar-2013
	ABS 4-Inch Circle Cut Endcaps	00013-01	02	14	EA	O	Tap Plastics	Custom	$6.31	$88.34	Jake	1	1	0	0		23-Sept-2012	6-Mar-2013
	Black Spray Paint Finish		N/A	1	EA	B	Kelly-Moore	N/A	$9.42	$9.42	Jake	0	0	0	0		4-Oct-2012	6-Mar-2013
	Aluminum Foil Tape	76055A23	N/A	3	Roll	B	McMaster-Carr	76055A23	$12.80	$38.40								
	SCIGrip ABS Cement 4707		N/A	1	OZ	B	Tap Plastics	N/A	$20.59	$20.59	Jake	0	0	0	0		4-Oct-2012	6-Mar-2013
	↦ Louver Assembly	M0002-01	01	1	EA	M					Team	34	0	24	0	10	15-Nov-2012	9-May-2013
	Subsystem Total									**$228.62**		**40.5**						
Phase Change Material Core																		
	RT28 HC PCM + Shipping (International)	00016	N/A	1	Drum	B	Rubitherm Technologies		$1,000.00	$1,000.00	Quin	1	0	1 [4]	0		15-Nov-2012	7-Mar-2013
	↦ PCM Assembly	M0003	N/A	1	EA	M					Quin	6	1	0	0	5 [5]	6-Mar-2013	7-Mar-2013
	Subsystem Total									**$1,000.00**		**7**						
Base Assembly																		
	Welded Frame Sub-Assembly	00041-01	02	1	EA	M/O	Sims Metal Management	N/A	$150.00	$150.00	Team	50	5	0	45		10-Jan-2013	22-Jan-2013
	↦ Steel Tube	00057-XX	01														10-Jan-2013	22-Jan-2013
	Support Sheet Top Edge	00044-01	01	3	EA	M	McMaster-Carr	8974K33	$8.66	$25.98	Team	7	1	0	2		23-Jan-2013	29-Apr-2013
	Drive Rod	00028-01	02	1	EA	M/O	McMaster-Carr	8974K33	$0.65	$0.65	Team	1.5	0.5	0	1		23-Jan-2013	29-Apr-2013
	Post Bottom	00029-01	02	7	EA	M/O	McMaster-Carr	8974K33	$0.80	$5.60	Team	4	0.5	0	0.5		23-Jan-2013	1-May-2013
	PVC Plate	00052-01	01	1	EA	M/O	McMaster-Carr	8974K33	$5.29	$5.29	Team	1	0.5	0	0.5		23-Jan-2013	1-May-2013
	Support Sheet Bottom	00035-01	02	4	EA	M	McMaster-Carr	8974K33	$5.35	$21.40	Team	6.5	0.5	0	1.5		14-Feb-2013	3-May-2013
	Support Sheet Edge Bottom	00036-01	02	2	EA	M	McMaster-Carr	8974K33	$5.35	$10.70	Team	3.5	0.5	0	1.5		14-Feb-2013	6-May-2013
	Support Sheet Middle Bottom	00037-01	02	1	EA	M	McMaster-Carr	8974K33	$2.67	$2.67	Team	1.5	0.5	0	1		14-Feb-2013	6-May-2013
	Support Sheet Top	00039-01	02	4	EA	M	McMaster-Carr	8974K33	$8.66	$34.64	Team	9	1	0	2		14-Feb-2013	6-May-2013
	Top Sheet	00040-01	02	1	EA	M/O	McMaster-Carr	N/A	$50.00	$50.00	Team	5	1	0	4		21-Feb-2013	7-May-2013
	Worm Gear	00042-01	01	10	EA	M/O	McMaster-Carr	5172721	$20.10	$201.00	Team	3.5	1	0	0.25		21-Feb-2013	7-May-2013
	End Post	00047-01	01	2	EA	M	McMaster-Carr	8974K33	$0.65	$1.30	Team	1.5	0.5	0	0.5		21-Feb-2013	7-May-2013
	Spacer	00050-01	01	2	EA	M/O	McMaster-Carr	8627K539	$1.52	$3.04	Team	1	0.5	0	0.25		21-Feb-2013	7-May-2013
	Press Pin	00049-01	N/A	10	EA	B	McMaster-Carr	99010A127	$1.80	$18.00	Team	1	1	0	0		21-Feb-2013	7-May-2013
	↦ Base Assembly	M0004-01	01	1	EA	M					Team	12	0	24	0	10	16-Apr-2013	9-May-2013
	Subsystem Total									**$530.27**		**108**						
Bearing Assembly																		
	Rack Support	00030-01	02	1	EA	M	McMaster-Carr	8975K713	$17.23	$17.23	Team	2	1	0	1		14-Feb-2013	3-May-2013
	Rack	00031-01	N/A	2	EA	M/O	McMaster-Carr	5174T22	$32.23	$64.46	Team	2	1	0	1		14-Feb-2013	3-May-2013
	Bearing Support	00045-01	01	2	EA	M/O	McMaster-Carr	8975K713	$17.23	$34.46	Team	5	1	0	2		14-Feb-2013	3-May-2013
	Bearing Support Rod	00046-01	01	7	EA	M/O	Home Depot	N/A	$2.50	$17.50	Team	4.5	1	0	0.5		14-Feb-2013	7-May-2013
	End Support	00051-01	01	2	EA	M/O	McMaster-Carr	8975K713	$5.74	$11.48	Team	5	1	0	2		14-Feb-2013	7-May-2013
	↦ Bearing Assembly	M0005-01	01	1	EA	M					Team	34	0	24	0	10	6-May-2013	9-May-2013
	Subsystem Total									**$145.13**		**50.5**						
Top Assembly																		
	Top Block	00056-01	01	7	EA	M	McMaster-Carr	8739K43	$5.13	$35.91	Team	6	0.75	0	0.75		1-Apr-2013	8-May-2013
	Top End	00054-01	01	2	EA	M	McMaster-Carr	6527K414	$8.75	$17.50	Team	3	1	0	1		1-Apr-2013	7-May-2013
	Top Rail	00055-01	01	2	EA	M	McMaster-Carr	8975K17	$4.99	$9.98	Team	6	1	0	2.5		1-Apr-2013	8-May-2013
	Post Top	00053-01	01	7	EA	M	McMaster-Carr	8974K33	$0.65	$4.55	Team	2.5	0.75	0	0.25		1-Apr-2013	8-May-2013
	↦ Top Assembly	M0006-01	01	1	EA	M					Team	17.5	5	0	0	25	7-May-2013	9-May-2013
	Subsystem Total									**$67.94**		**35**						
Project Totals										**$2,167.42**		**266**						

[1] B = Bought, M = Made By You, O = Made By Others

[2] Total Team Hours in Design, Procurement, Manufacture, and Assembly

[3] Or By Description (Alternate Vendor May Be Used with Product Description Equivalency)
[4] Forced Melting of PCM to Change Consistency
[5] Pouring PCM into Louver Subsytem

Chapter A.10: Costflow Spreadsheet

Senior Design Costflow

PRJ01: Senior Design

Date	PR #	Vendor	Account	Purchased	Amount	Buyer	Fund		
1/1/2012							CSTS, LBNL, SOE		
2/1/2012									
3/1/2012									
4/1/2012									
5/1/2012									
6/1/2012									
7/1/2012									
8/1/2012									
9/1/2012									
9/29/2012		Home Depot		Paint and supplies for hutches	41.02	Alex	CSTS		
10/1/2012									
10/4/2012		Home Depot		Supplies for first prototype	$41.95	Jake	SRIG		
10/24/2012		Home Depot		Bolts, washers, and silicone for second prototype	$16.86	Jake	SRIG	$91.66	
10/29/2012		McMaster-Carr		Weather-stripping for prototype waterproofing	$21.69	Jake	SRIG		
10/31/2012		Tap Plastics		Cut to size acrylic and drill bit for plastic	$11.16	Jake	SRIG		
11/1/2012									
11/4/2012		OSH		Filters for PCM	10.69	Ali	LBNL		
11/4/2012		Ebay		Stepper Motor	155.34	Alex	LBNL		
11/6/2012		McMaster-Carr		Components for louver and controls system	143.12	Jake	LBNL		
11/7/2012		McMaster-Carr		Flange for controls system	73.82	Jake	LBNL		744.65
11/9/2012		Tap Plastics		ABS endcaps and acrylic face	71.01	Jake	LBNL		152.29
11/9/2012		Home Depot		Pipe and hardware	36.98	Jake	LBNL		
11/12/2012		McMaster-Carr		More weather stripping	46.31	Jake	LBNL		
11/12/2012		Tap Plastics		ABS cement	20.59	Jake	LBNL		
11/13/2012		Michaels		Wax	7.58	Ali	LBNL		
11/16/2012		Home Depot		Longer Bolts	1.56	Ali	LBNL		
11/16/2012		Adafruit Industries		Stepper, and controls hardware	56.67	Alex	LBNL		
11/18/2012		SparkFun		Arduino Mega	85.23	Alex	LBNL		
11/19/2012		Tap Plastics		ABS Half Circle	15.09	Jake	LBNL		
11/21/2012		Sims Group		Metal for stand	78.25	Ali	CSTS		
11/27/2012		Tap Plastics		Acrylic Faces	20.86	Jake	LBNL		
12/1/2012									
12/6/2012		Tap Plastics		More Plastic	20.93	Jake	CSTS		
12/11/2012		Rubitherm PCMs		Waxes	459.99	Quin	CSTS		
12/18/2012		Kelly-Moore		Black spraypaint for acrylic face	9.42	Jake	CSTS		
1/1/2013									
1/6/2013		Lowe's		Connections for site power	31.98	Fr. Reites	SOE		
1/11/2013		Tap Plastics		Plastic tubes for wax storage	27.59	Ali	CSTS		
1/13/2013		Radio Shack		Controls components	26.67	Alex	CSTS		
1/13/2013		Radio Shack		Controls components	18.46	Alex	CSTS		
1/15/2013		Radio Shack		Controls accessories and cushion feet	11.47	Alex	CSTS		$5645.24
1/18/2013		McMaster-Carr		Couplings for stepper	95.26	Jake	CSTS		
1/18/2013		Home Depot		Keys	7.03	Jake	CSTS		
1/22/2013		McMaster-Carr		Threaded Flange	40.24	Jake	CSTS		
1/24/2013		Home Depot		acrylic, keys, bolts, and lube	83.57	Jake	CSTS		
1/25/2013		Home Depot		keys	4.06	Jake	CSTS		
1/27/2013		McMaster-Carr		Compression fitting, flange, spur gears, nylon, u-channel, and steel sheet	321.29	Jake	CSTS		
1/28/2013		Walmart.com		Space heaters	210.75	Ali	CSTS		
1/29/2013		McMaster-Carr		Spur gears	92.57	Jake	CSTS		
1/30/2013		Tap Plastics		ABS encaps and acrylic faces	22.31	Jake	CSTS		
1/30/2013		McMaster-Carr		Aluminum tape	14.94	Jake	CSTS		
2/1/2013									
2/3/2013		Amazon		Power supplies	454.52	Ali	CSTS		
2/7/2013		Rubitherm		Bulk wax	2198.01	Quin	CSTS		
2/7/2013		Rubitherm		Bulk wax	Split with above	Quin	SOE		
2/15/2013		McMaster-Carr		Roller Bearing	43.94	Jake	LBNL		
2/19/2013		McMaster-Carr		Components for second prototype	328.24	Jake	LBNL	Which items do these include?	

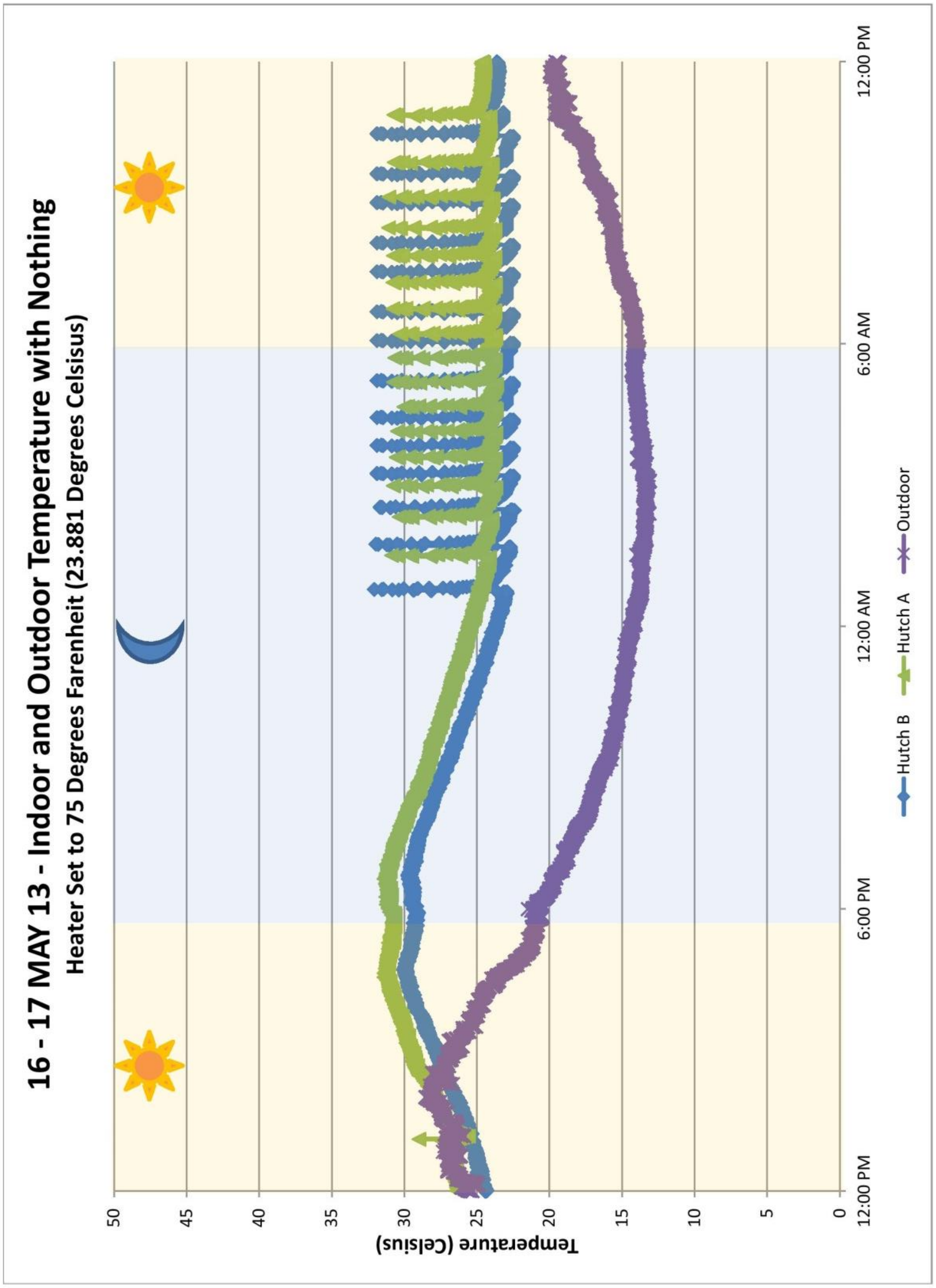
Fund Strings	Account	Fund	Dept ID	Programn	Proj/Grant	Class	
CSTS	6502	14008	MECH	RSCH	12ROEL03		2500
LBNL		13001	MECH	RSCH	LBNL04		15000
SOE		11001	ENGSCL	ENGSP	IN	FAC18	2000

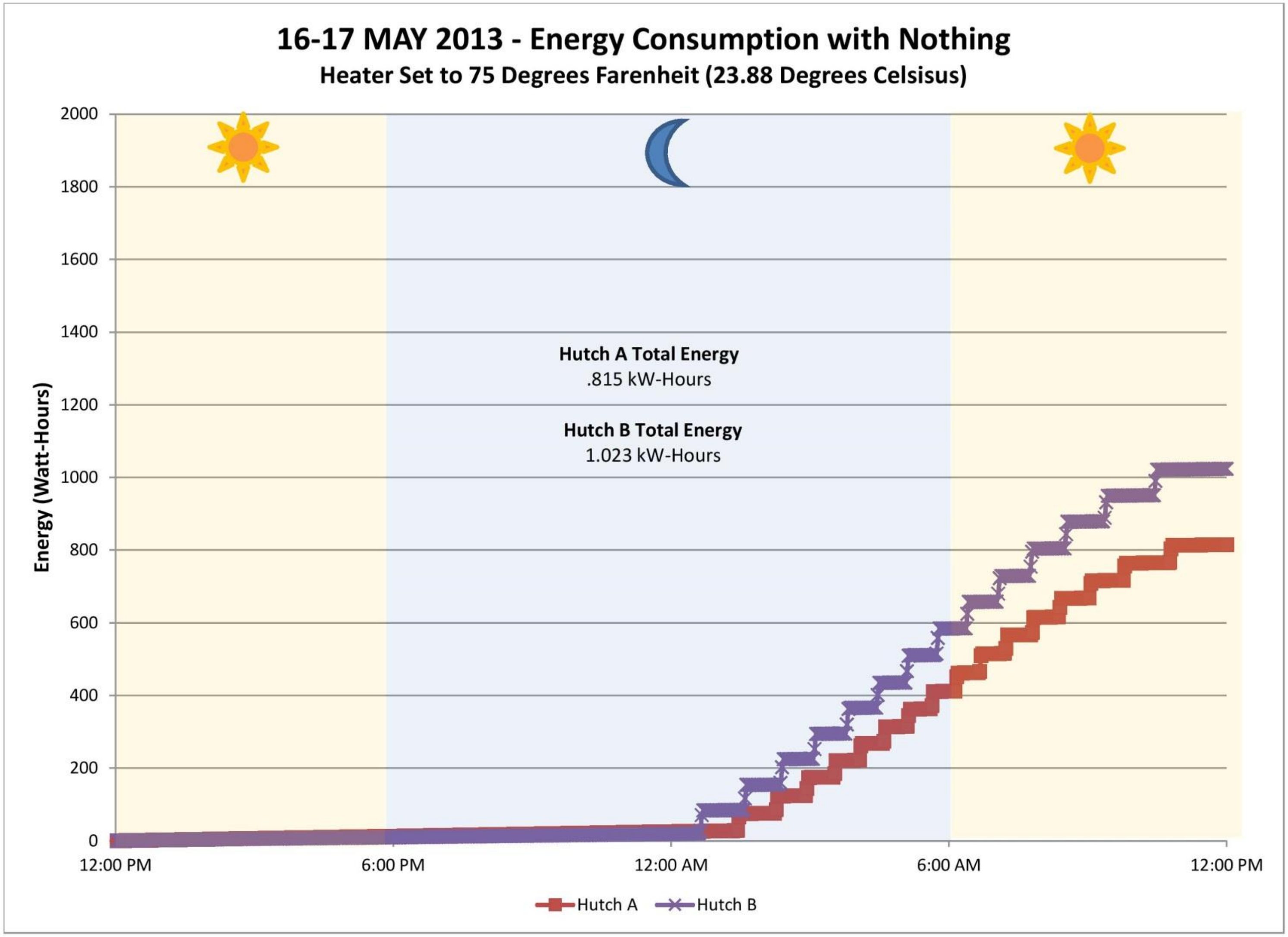
1

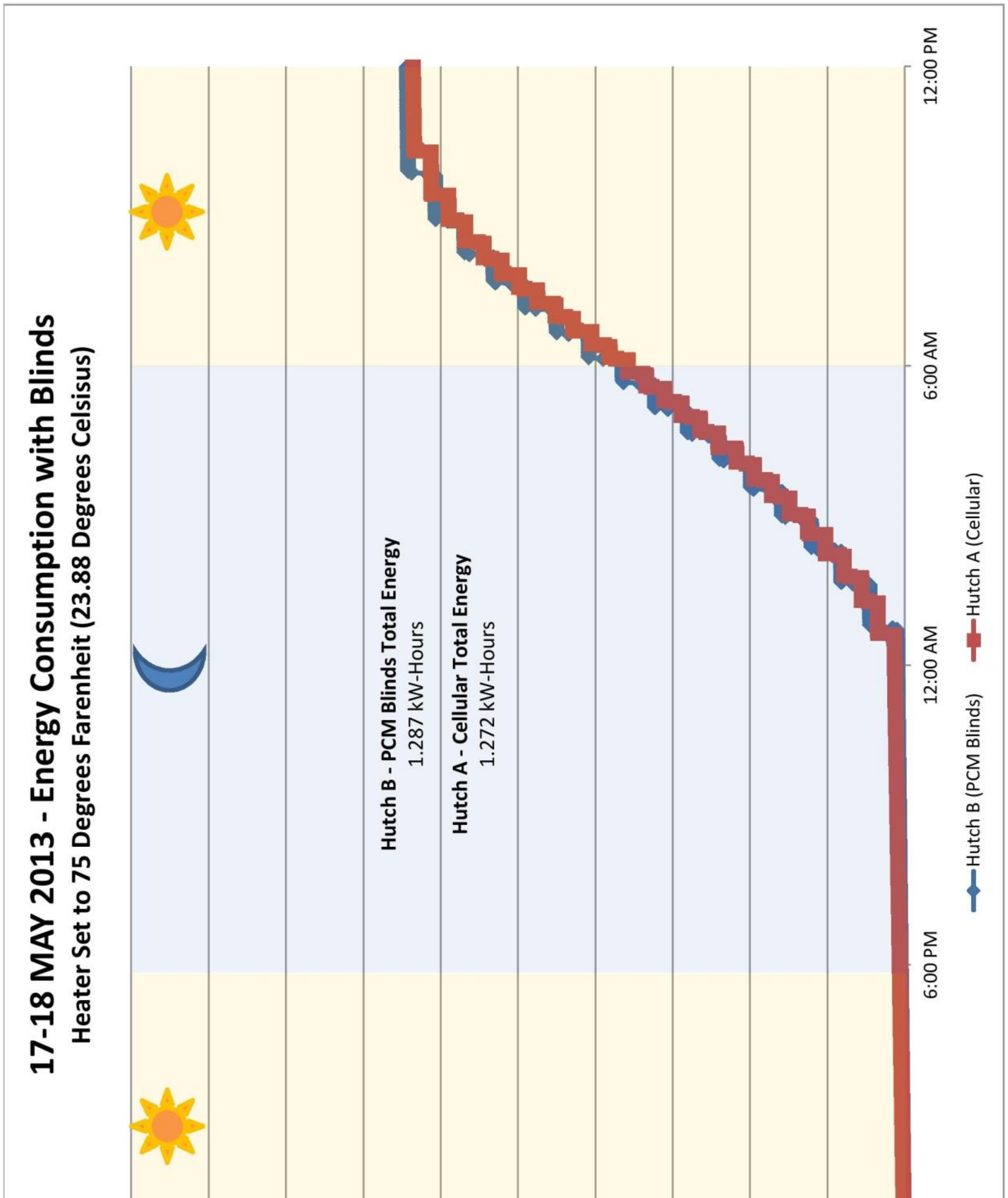
2/20/2013		McMaster-Carr		Foil and masking tape	16.07	Jake	LBNL		
2/21/2013		Home Depot		Epoxy and ABS	40.72	Jake	LBNL		
2/23/2013		Tap Plastics		Acrylic, masking tape and ABS endcaps	63.32	Jake	LBNL		
2/26/2013		McMaster-Carr		Nylon bearing materials	28.5	Jake	LBNL		
2/26/2013		SparkFun		Servo	17.81	Jake	LBNL		
3/1/2013								832.42	
3/5/2013		Tap		Glue	9.56	Jake	LBNL		
3/7/2013		Hobbytown		Servo	21.72	Alex	SOE		
3/15/2013		Home Depot		Pump & Paint	43.71	Jake	LBNL		
3/15/2013		Tap		Acrylic	14.18	Jake	LBNL		
3/19/2013		Sims Group		Steel tubing	11.73	Ali	LBNL		
4/1/2013									
4/1/2013		Best Buy		USB Cable	21.73	Ali	LBNL		
4/5/2013		McMaster		Return of unused parts	-67.68	Jake	LBNL		
4/8/2013		Enco		Extended drill bit	18.29	Jake	LBNL		
4/8/2013		McMaster		Foil Tape	47.23	Jake	LBNL		
4/8/2013		SparkFun		Arduino Uno	86.12	Jake	LBNL		
4/10/2013		McMaster		Loctite retaining compound	41.33	Jake	LBNL		
4/10/2013		SparkFun		Wiring	34.57	Alex	LBNL		
4/11/2013		Home Depot		Machine screws	8.98	Jake	LBNL		
4/11/2013		Home Depot		Machine screws	2.35	Jake	LBNL		
4/15/2013		Sims Group		Steel tubing	30.67	Ali	LBNL		
4/18/2013		NI		CompactDAQ	294.49	Jake	LBNL		
4/19/2013		McMaster		tons of hardware for final system	740.65	Jake	LBNL		
4/22/2013		McMaster		aluminum for final system	109.97	Jake	LBNL	Alex	107.99
4/22/2013		SparkFun		clock module	41.17	Alex	LBNL	Ali	756.74
4/23/2013		ServoCity		Servo motor	166.97	Jake	LBNL	Quin	101.06
4/23/2013		McMaster		Steel tube	24.71	Jake	LBNL	Fr. Reites	31.98
4/24/2013		NI		CompactDAQ	21.74	Jake	LBNL		
4/25/2013		NI		CompactDAQ	272.75	Jake	LBNL		
4/29/2013		Amazon		Laptop	572.98	Ali	LBNL		
4/30/2013		Radioshack		Battery Adapter	10.53	Alex	SOE		
5/1/2013									
5/2/2013		Tap Plastics		ABS endcaps	101.06	Quin	LBNL		
5/6/2013		McMaster		Fasteners	789.77	Jake	LBNL		
5/6/2013		McMaster		Delrin	8.14	Jake	LBNL		
5/7/2013		McMaster		Fasteners	26.76	Jake	LBNL		
5/7/2013		Tap Plastics		acrylic glue	9.57	Jake	LBNL		
5/8/2013		Lowe's		Files and machine screws	31.1	Jake	LBNL		
5/14/2013		Target		Fan	70.68	Ali	LBNL		
5/14/2013		Target		Fan	70.68	Ali	LBNL		
5/16/2013		Lowe's		Control blinds	150.01	Ali	LBNL		
6/1/2013									
7/1/2013									
8/1/2013									
				Total:	$9483.46				
				Minus SOE & CSTS	$4983.46				

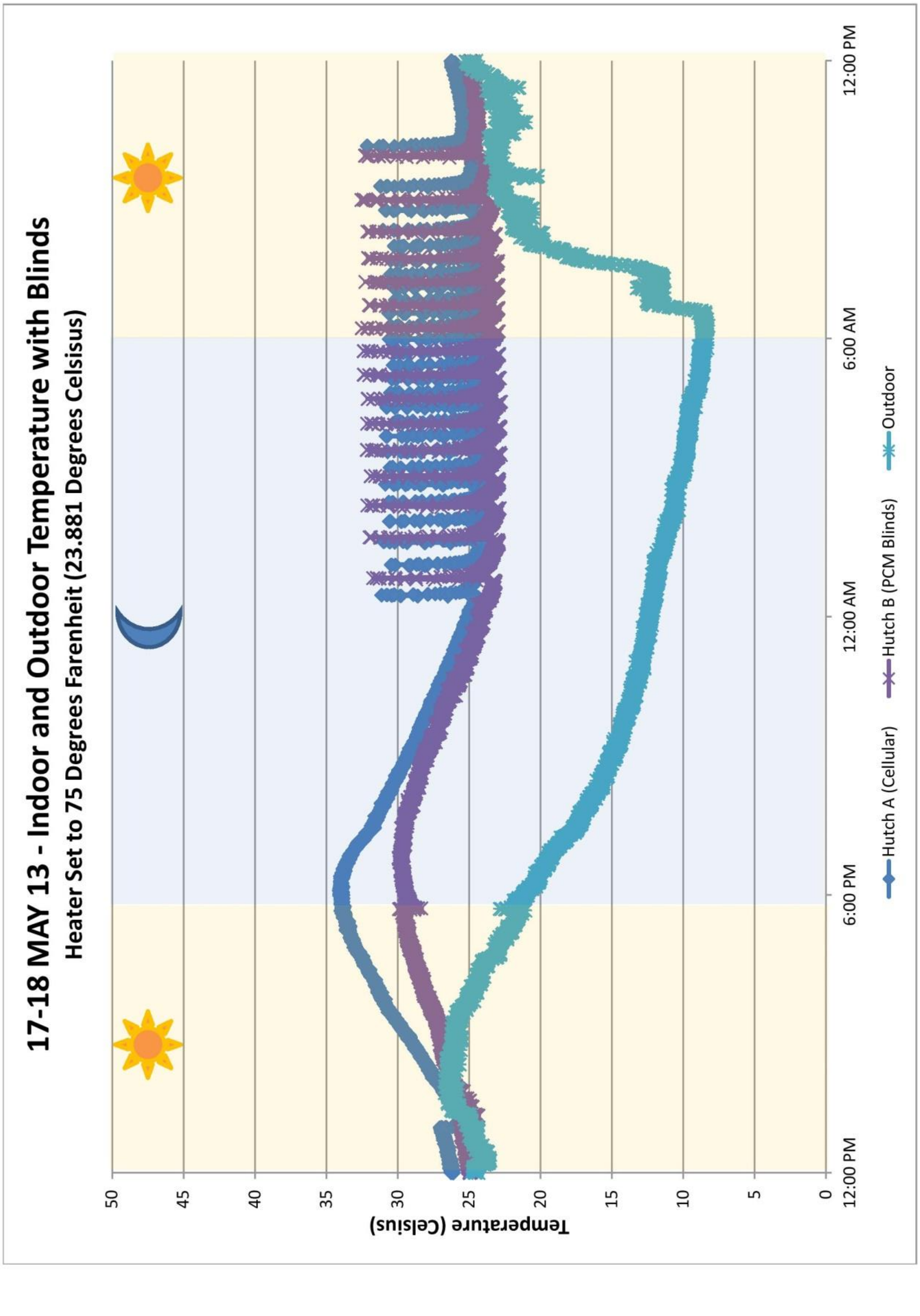
2

Appendix A.11: Experimental Data

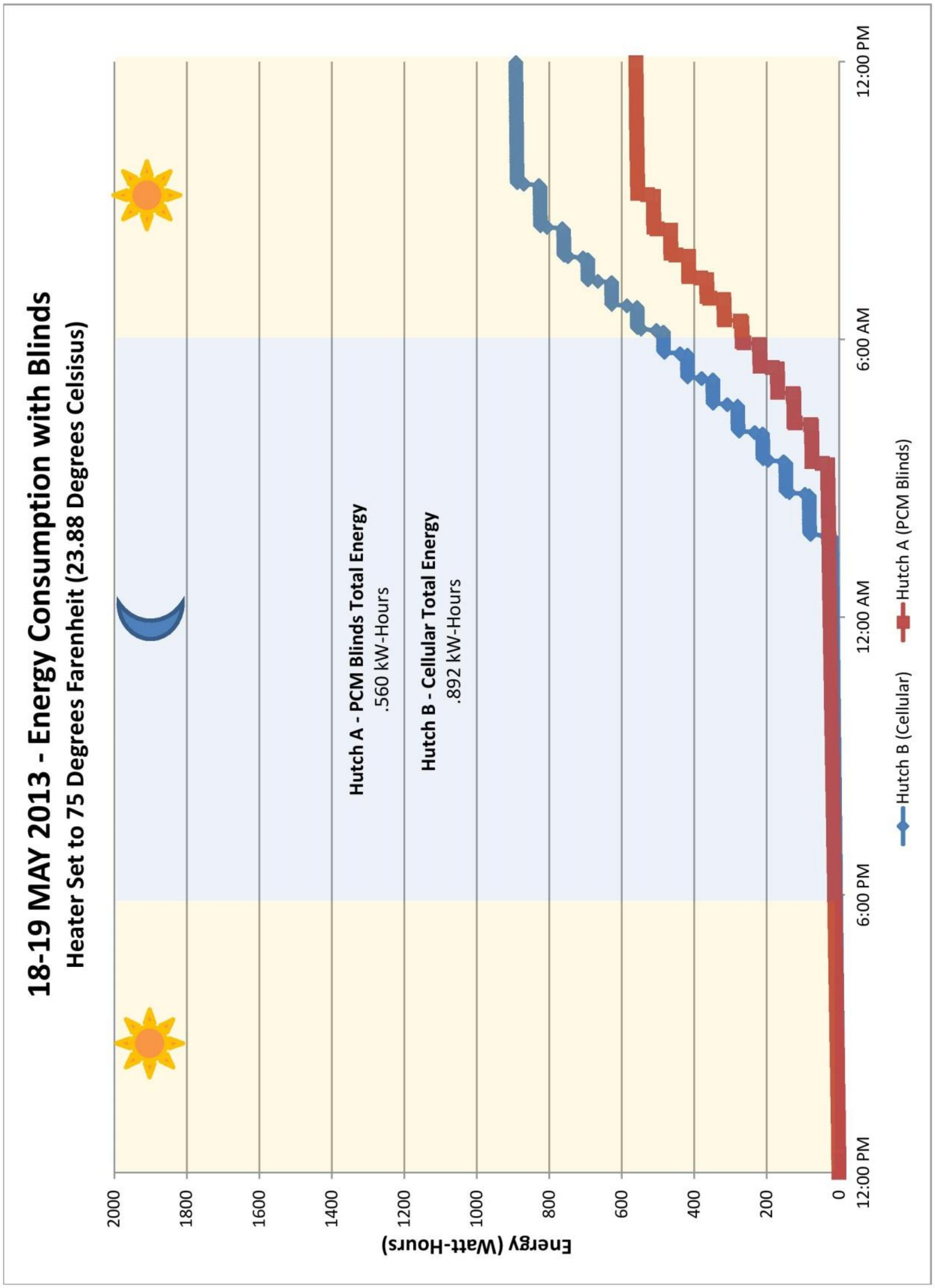



16-17 MAY 2013 - Energy Consumption with Nothing
Heater Set to 75 Degrees Farenheit (23.88 Degrees Celsisus)
Energy (Watt-Hours)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch A Total Energy
.815 kW-Hours
Hutch B Total Energy
1.023 kW-Hours
Hutch A
Hutch B

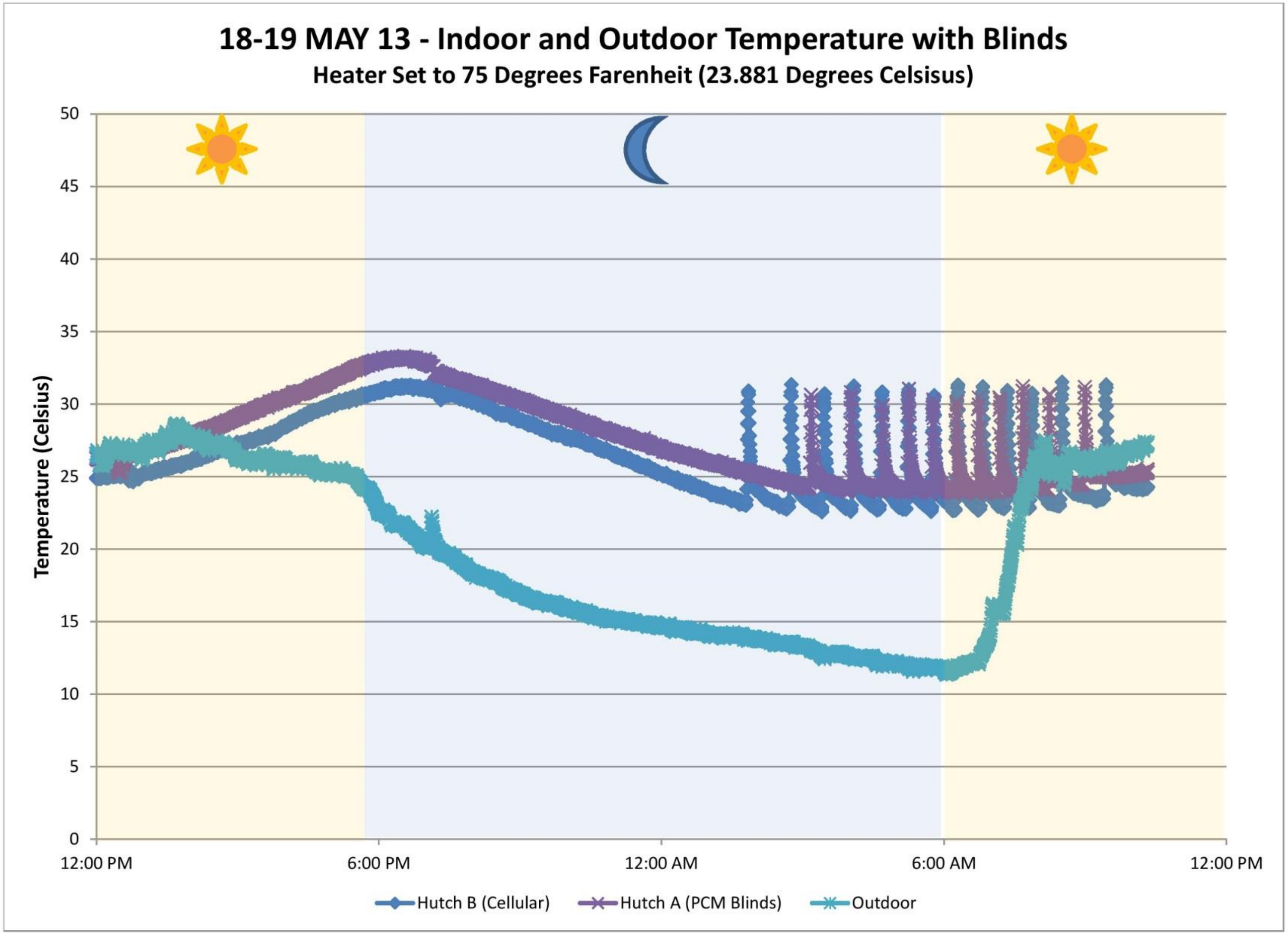

17-18 MAY 2013 - Energy Consumption with Blinds
Heater Set to 75 Degrees Farenheit (23.88 Degrees Celsisus)
Hutch B - PCM Blinds Total Energy
1.287 kW-Hours
Hutch A - Cellular Total Energy
1.272 kW-Hours
Energy (Watt-Hours)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch B (PCM Blinds)
Hutch A (Cellular)

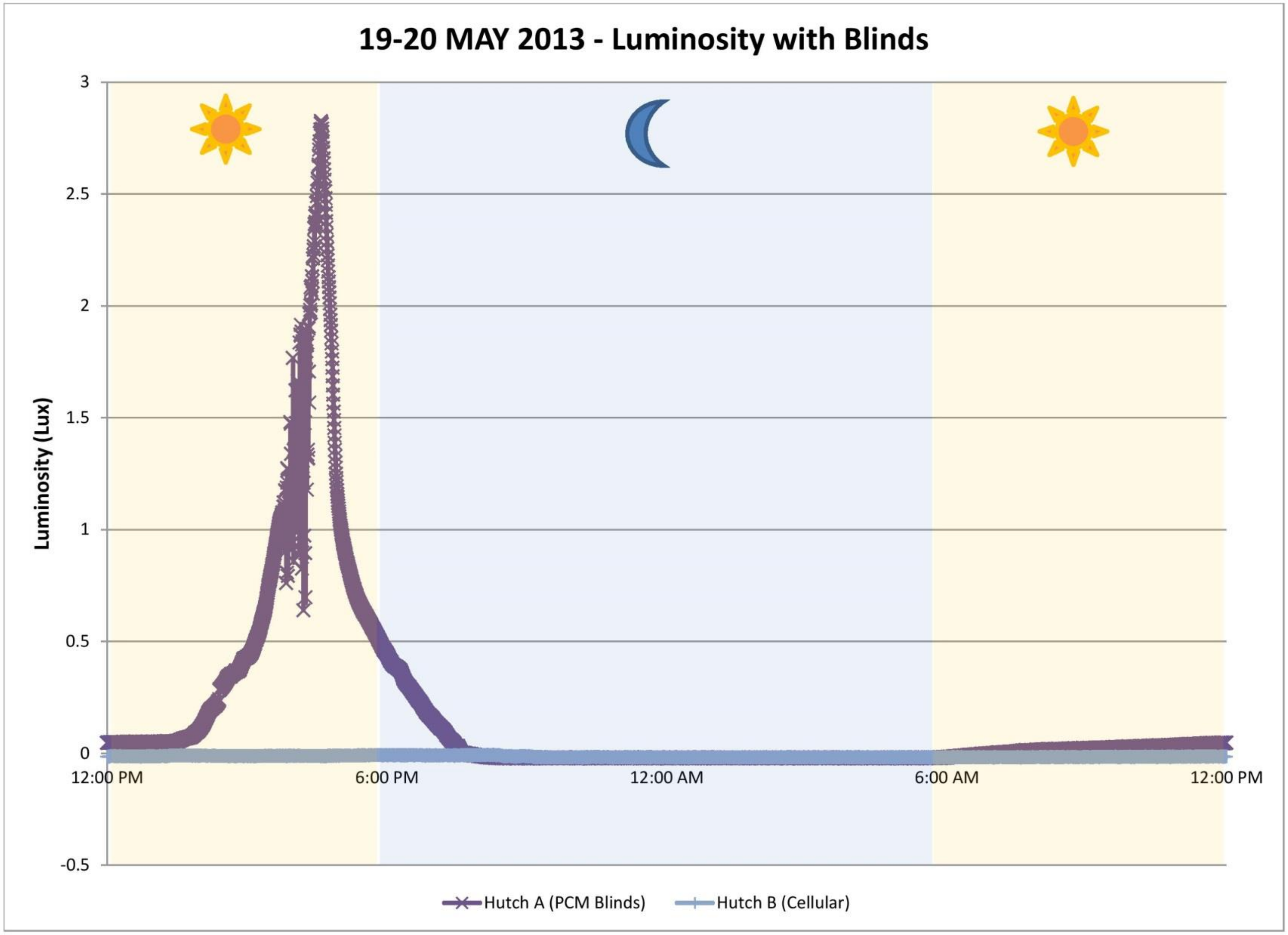


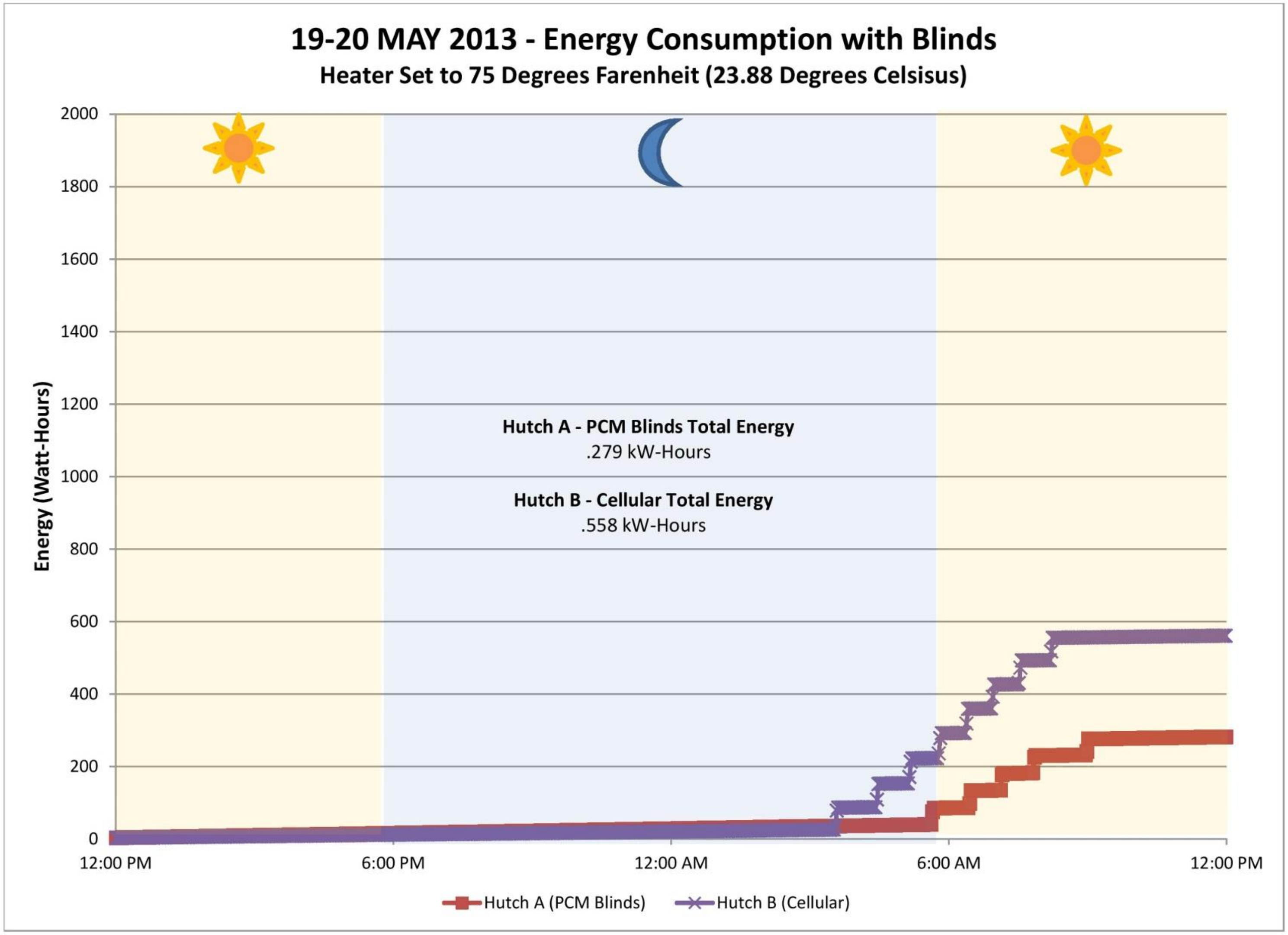
17-18 MAY 13 - Indoor and Outdoor Temperature with Blinds
Heater Set to 75 Degrees Farenheit (23.881 Degrees Celsisus)
Temperature (Celsius)
50
45
40
35
30
25
20
15
10
5
0
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch A (Cellular)
Hutch B (PCM Blinds)
Outdoor

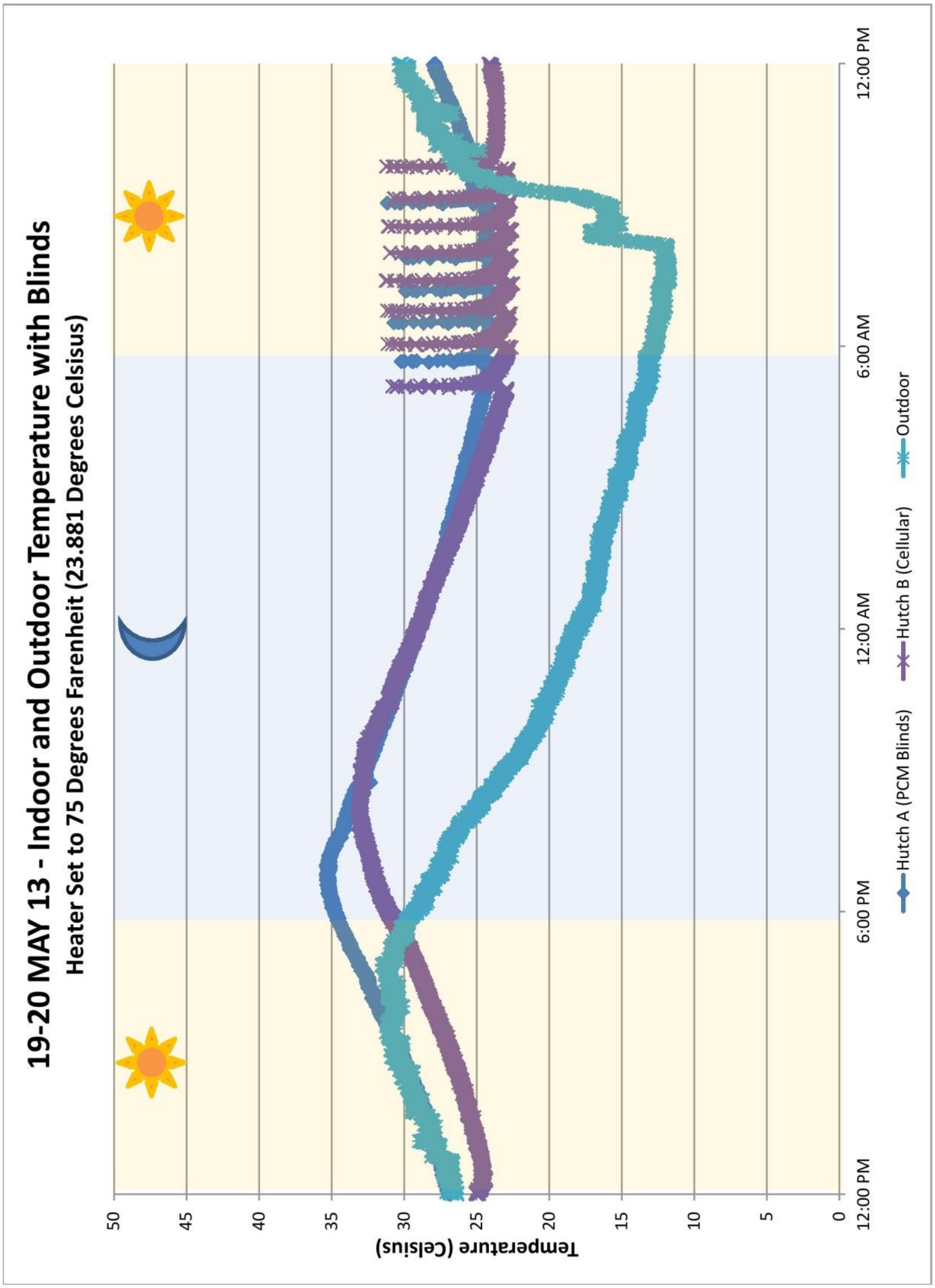


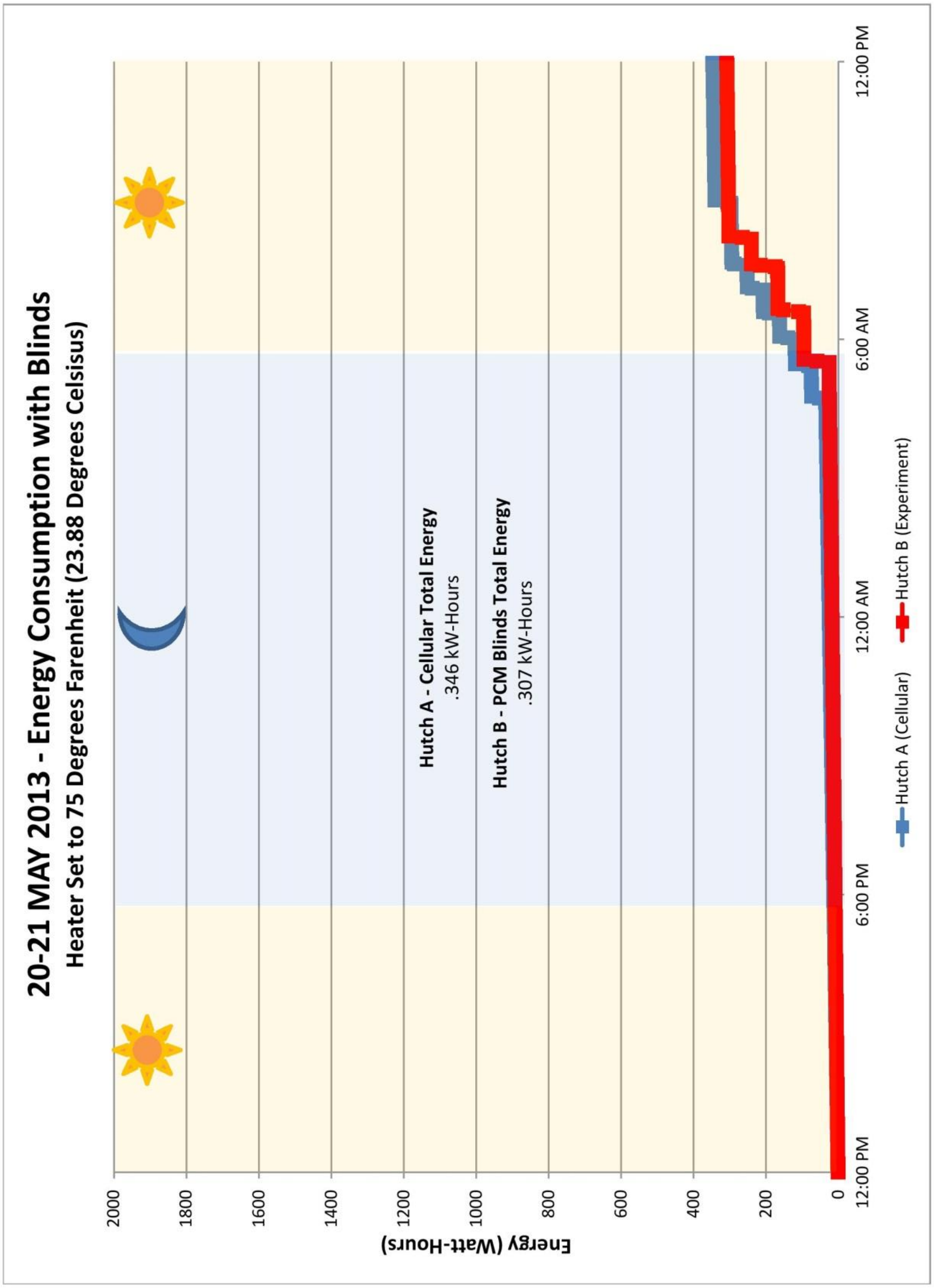
18-19 MAY 2013 - Energy Consumption with Blinds
Heater Set to 75 Degrees Farenheit (23.88 Degrees Celsisus)
Hutch A - PCM Blinds Total Energy
.560 kW-Hours
Hutch B - Cellular Total Energy
.892 kW-Hours
Energy (Watt-Hours)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch B (Cellular)
Hutch A (PCM Blinds)

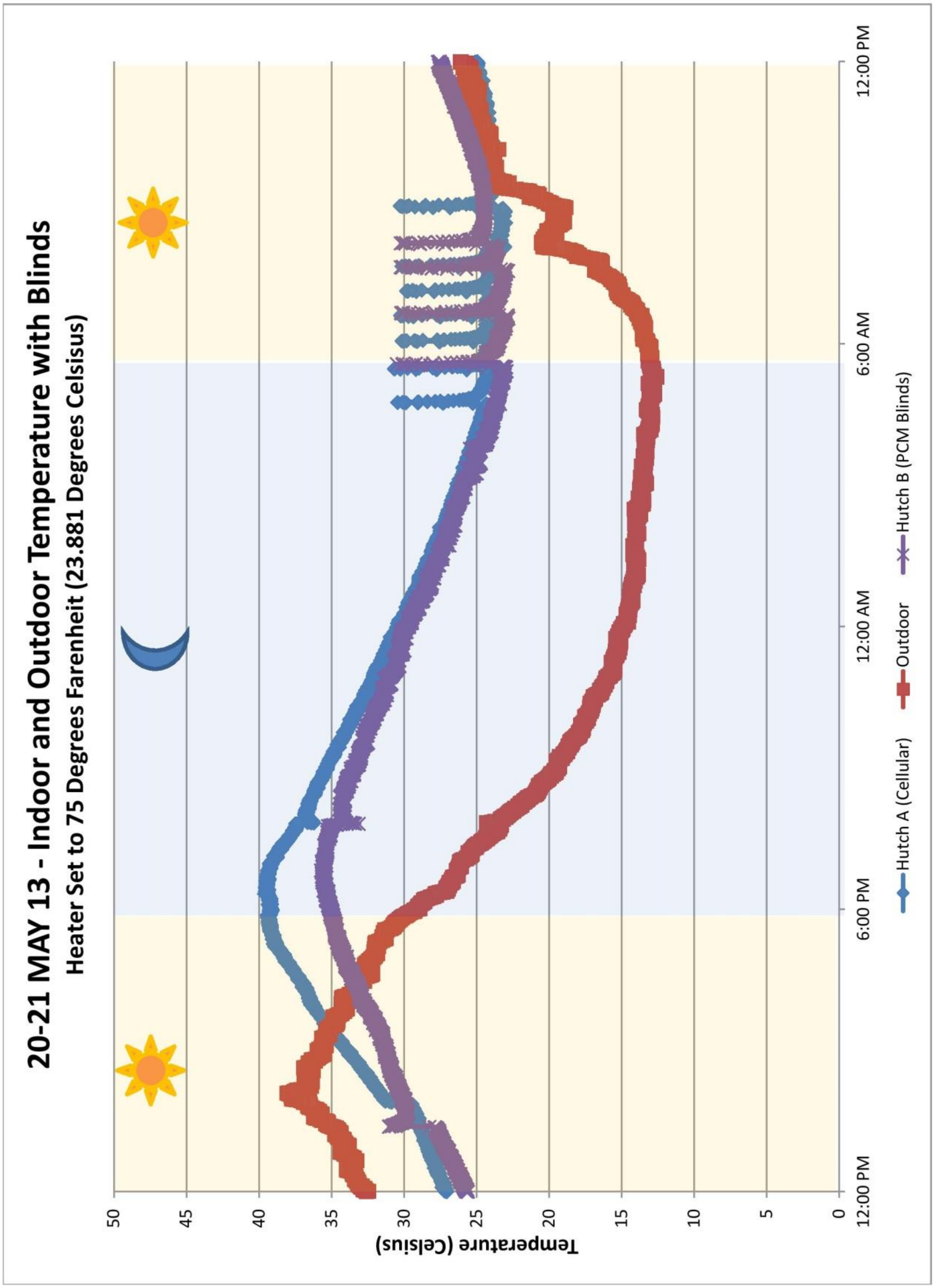

18-19 MAY 13 - Indoor and Outdoor Temperature with Blinds
Heater Set to 75 Degrees Farenheit (23.881 Degrees Celsisus)
Temperature (Celsius)
0
5
10
15
20
25
30
35
40
45
50
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch B (Cellular)
Hutch A (PCM Blinds)
Outdoor


19-20 MAY 2013 - Luminosity with Blinds
Luminosity (Lux)
3
2.5
2
1.5
1
0.5
0
-0.5
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch A (PCM Blinds)
Hutch B (Cellular)

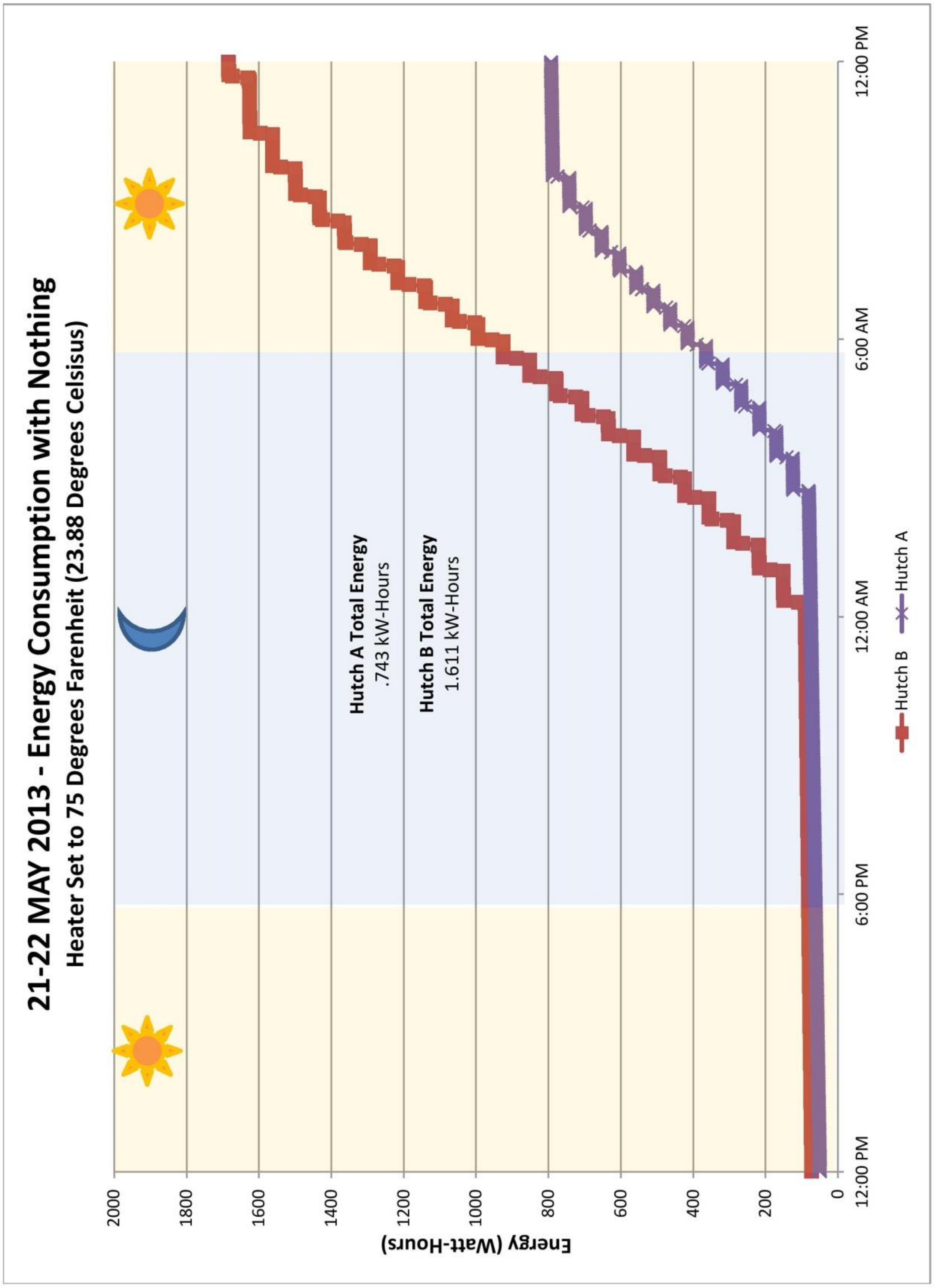

19-20 MAY 2013 - Energy Consumption with Blinds
Heater Set to 75 Degrees Farenheit (23.88 Degrees Celsisus)
Energy (Watt-Hours)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch A - PCM Blinds Total Energy
.279 kW-Hours
Hutch B - Cellular Total Energy
.558 kW-Hours
Hutch A (PCM Blinds)
Hutch B (Cellular)


19-20 MAY 13 - Indoor and Outdoor Temperature with Blinds
Heater Set to 75 Degrees Farenheit (23.881 Degrees Celsisus)
Temperature (Celsius)
50
45
40
35
30
25
20
15
10
5
0
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch A (PCM Blinds)
Hutch B (Cellular)
Outdoor

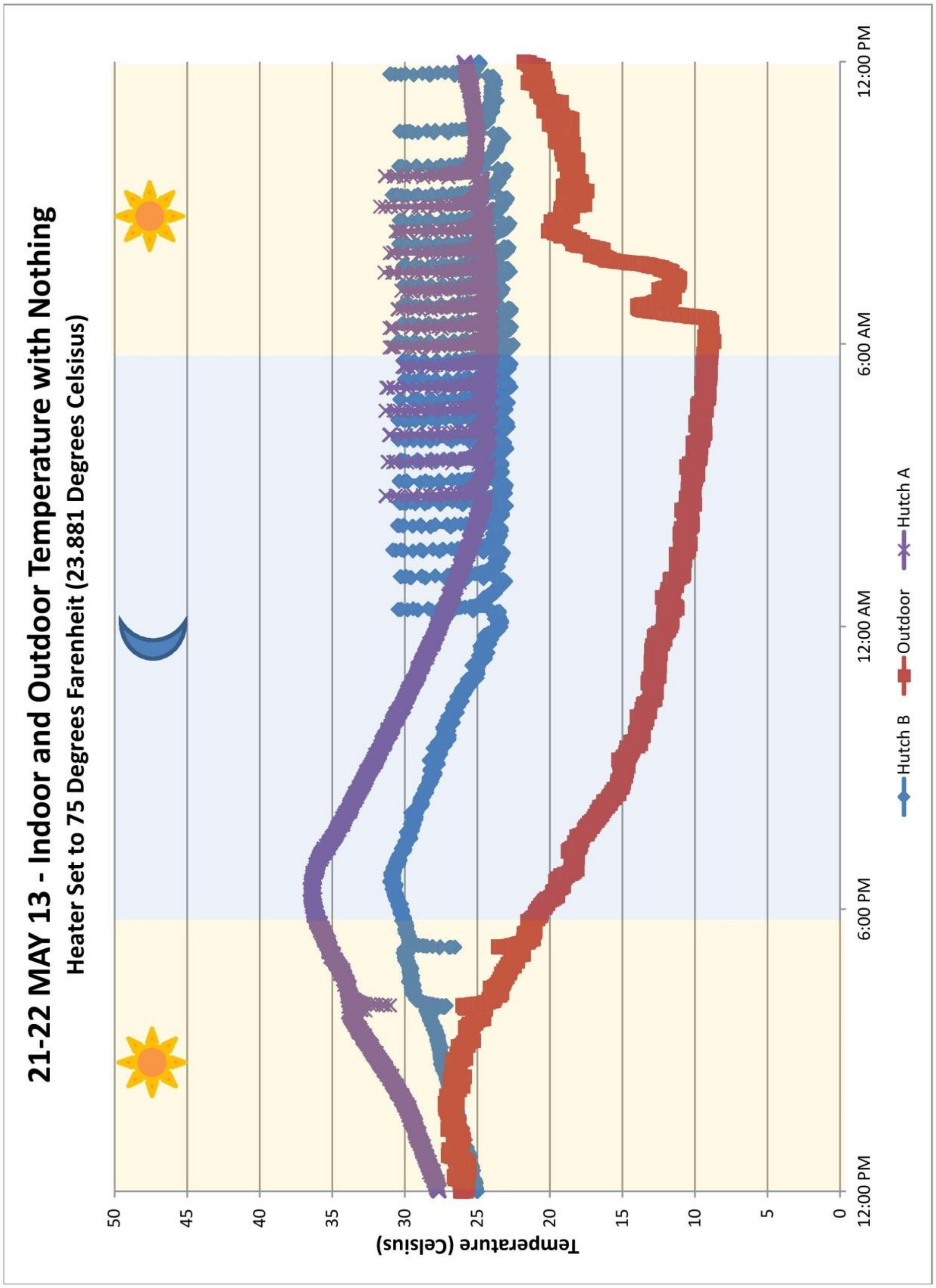

20-21 MAY 2013 - Energy Consumption with Blinds
Heater Set to 75 Degrees Farenheit (23.88 Degrees Celsisus)
Hutch A - Cellular Total Energy
.346 kW-Hours
Hutch B - PCM Blinds Total Energy
.307 kW-Hours
Energy (Watt-Hours)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch A (Cellular)
Hutch B (Experiment)

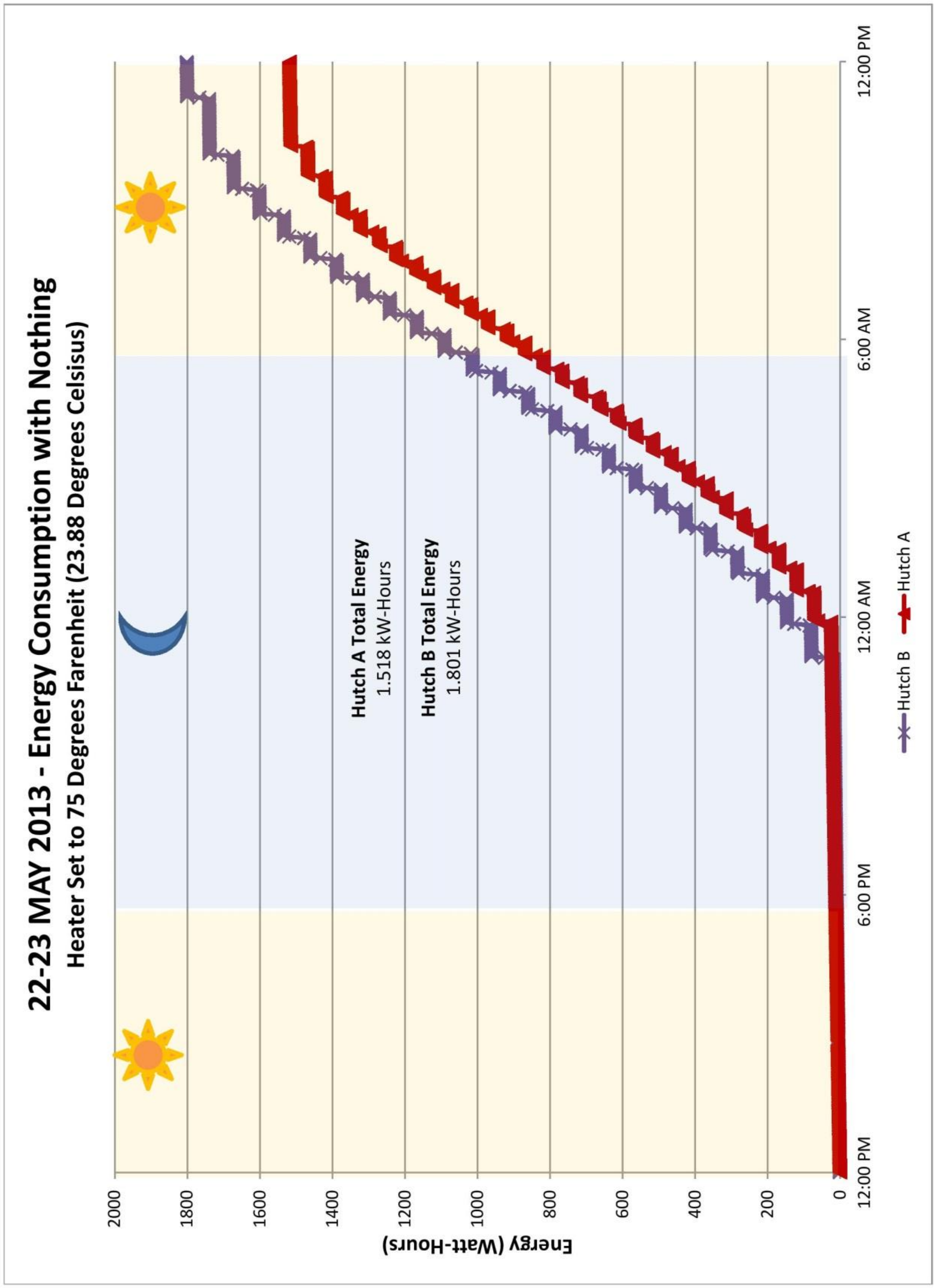


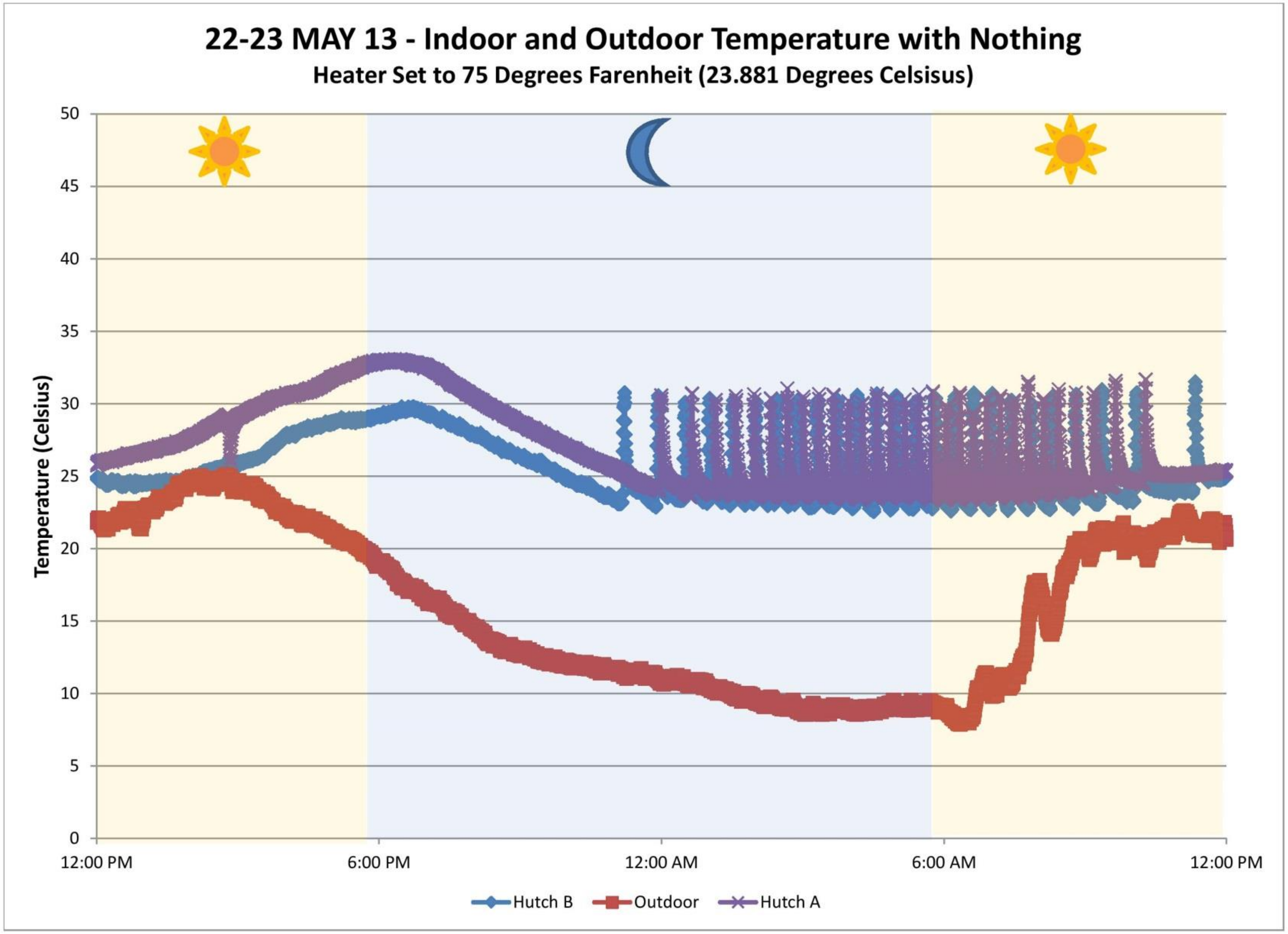
20-21 MAY 13 - Indoor and Outdoor Temperature with Blinds
Heater Set to 75 Degrees Farenheit (23.881 Degrees Celsisus)
Temperature (Celsius)
50
45
40
35
30
25
20
15
10
5
0
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch A (Cellular)
Outdoor
Hutch B (PCM Blinds)

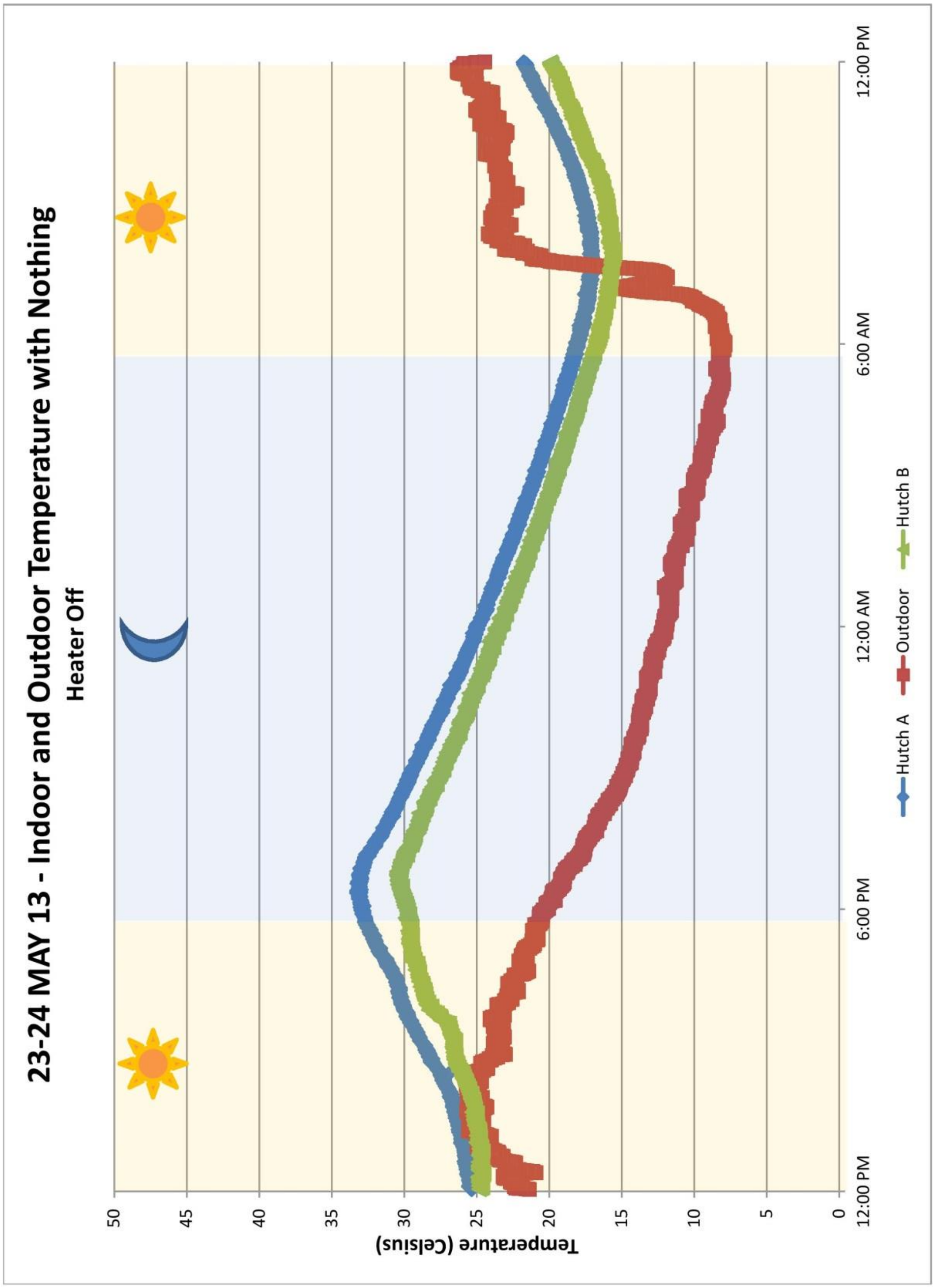


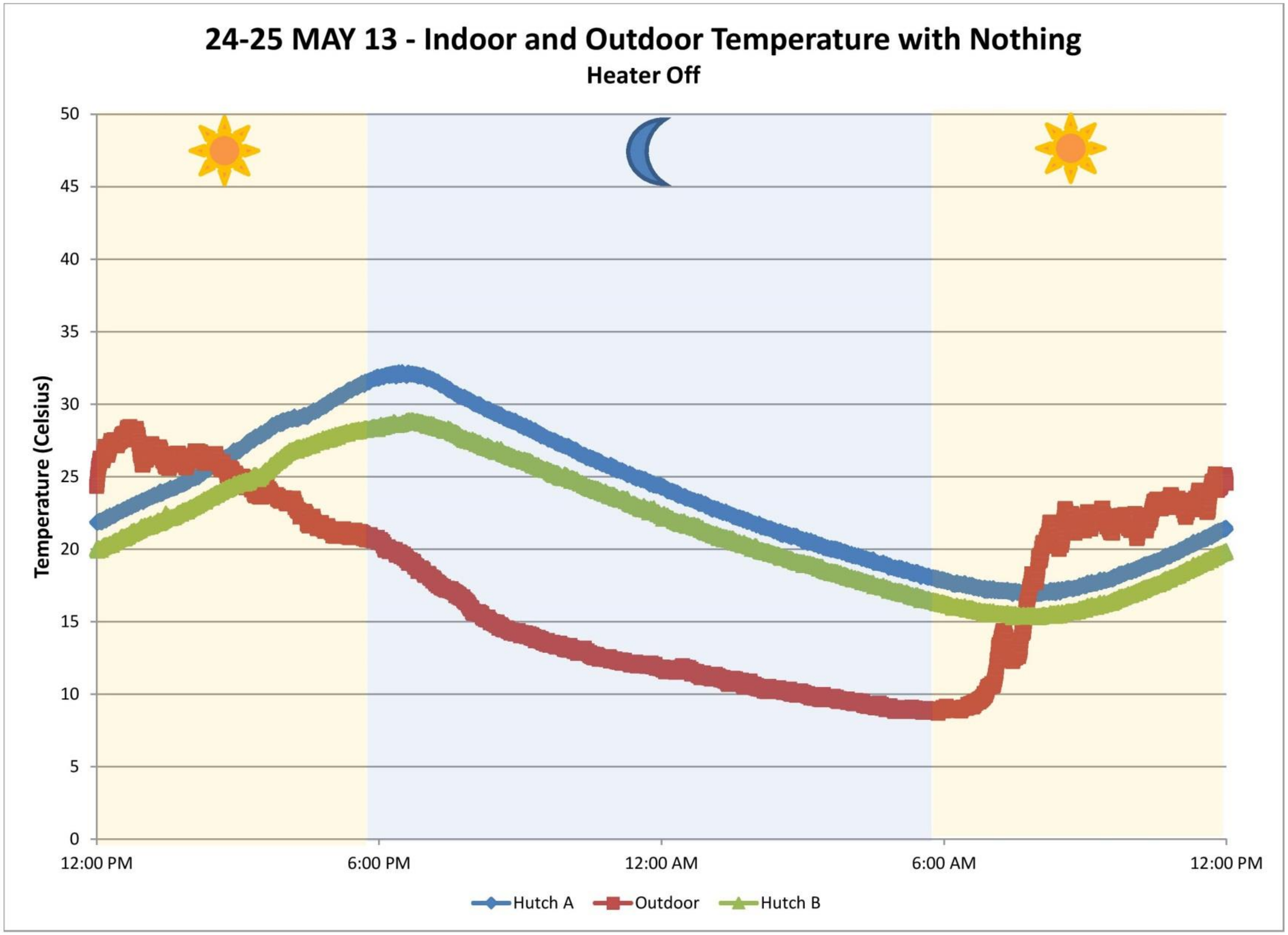
21-22 MAY 2013 - Energy Consumption with Nothing
Heater Set to 75 Degrees Farenheit (23.88 Degrees Celsisus)
Hutch A Total Energy
.743 kW-Hours
Hutch B Total Energy
1.611 kW-Hours
Energy (Watt-Hours)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch B
Hutch A

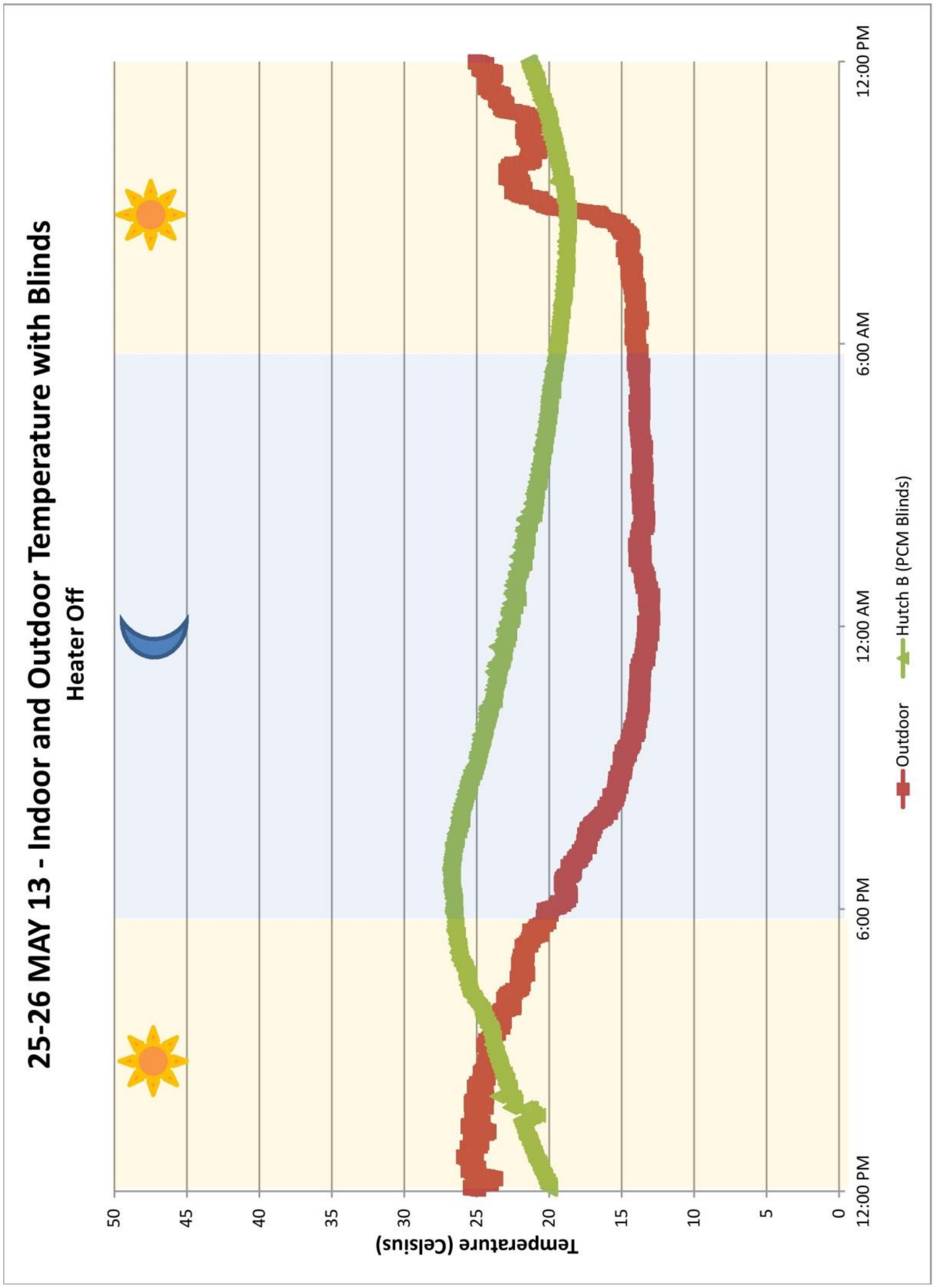

21-22 MAY 13 - Indoor and Outdoor Temperature with Nothing
Heater Set to 75 Degrees Farenheit (23.881 Degrees Celsisus)
Temperature (Celsius)
0
5
10
15
20
25
30
35
40
45
50
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch B
Outdoor
Hutch A

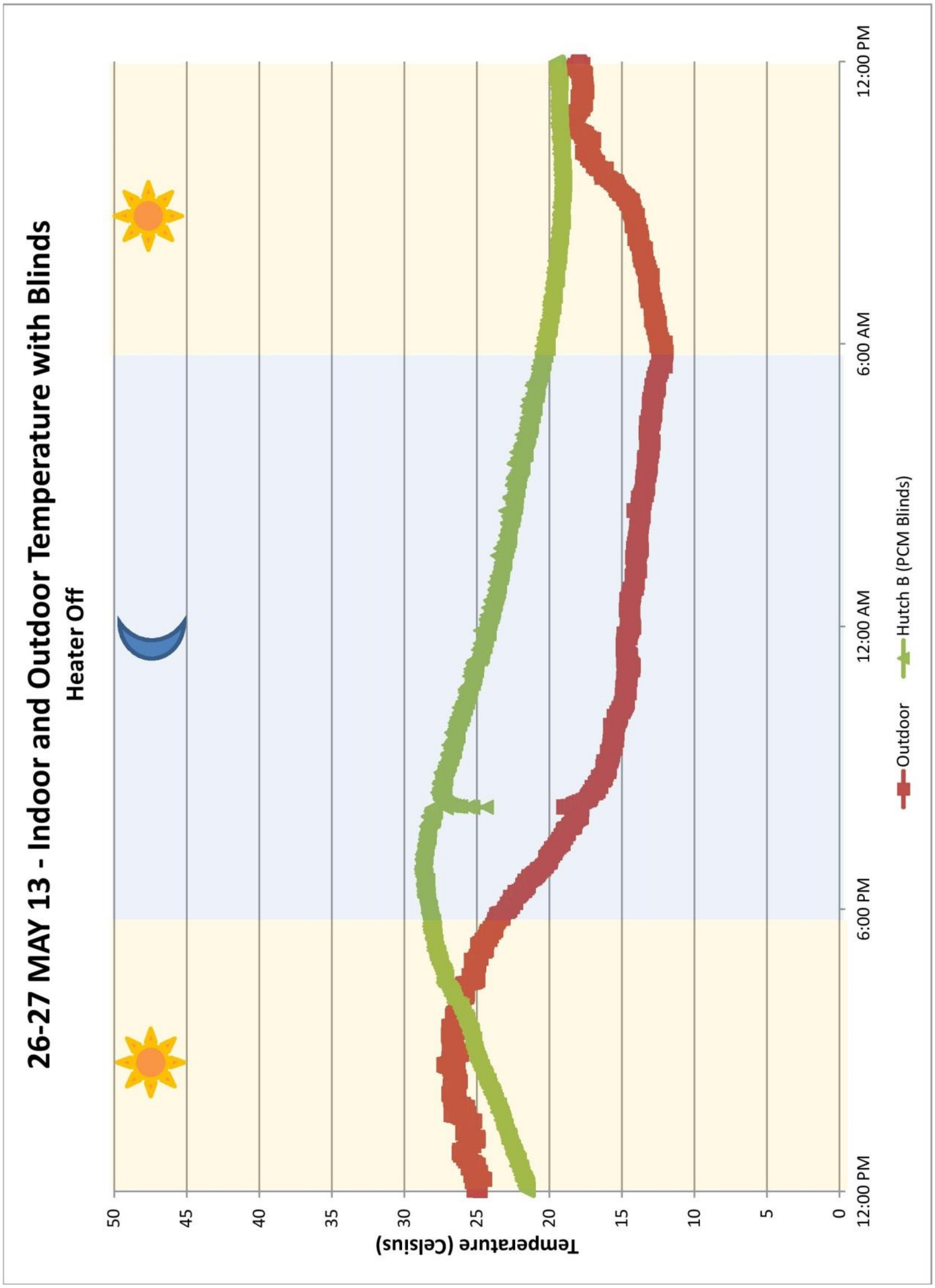

22-23 MAY 2013 - Energy Consumption with Nothing
Heater Set to 75 Degrees Farenheit (23.88 Degrees Celsisus)
Energy (Watt-Hours)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch A Total Energy
1.518 kW-Hours
Hutch B Total Energy
1.801 kW-Hours
Hutch B
Hutch A

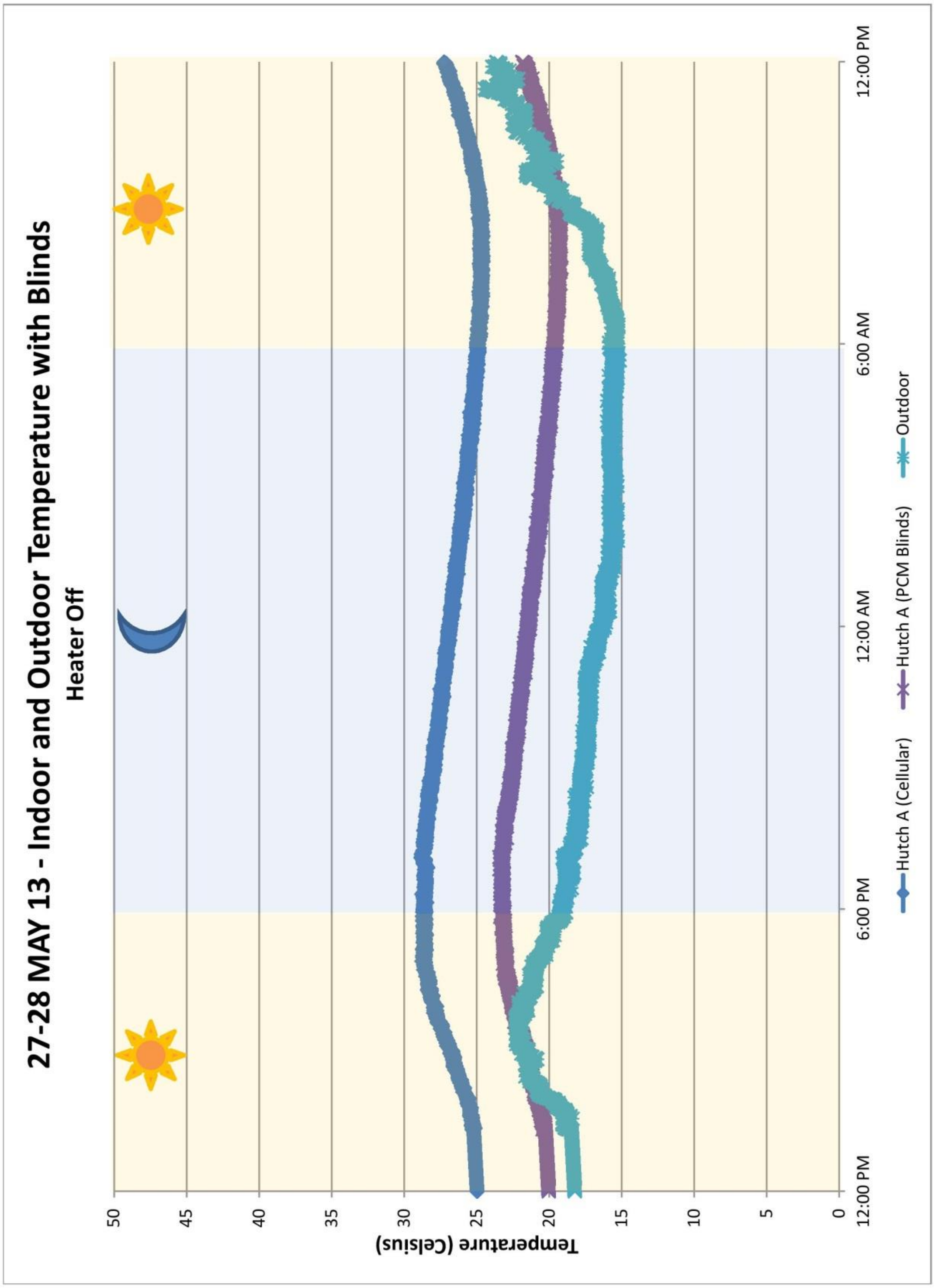

22-23 MAY 13 - Indoor and Outdoor Temperature with Nothing
Heater Set to 75 Degrees Farenheit (23.881 Degrees Celsisus)
Temperature (Celsius)
50
45
40
35
30
25
20
15
10
5
0
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch B
Outdoor
Hutch A


23-24 MAY 13 - Indoor and Outdoor Temperature with Nothing
Heater Off
Temperature (Celsius)
0
5
10
15
20
25
30
35
40
45
50
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch A
Outdoor
Hutch B

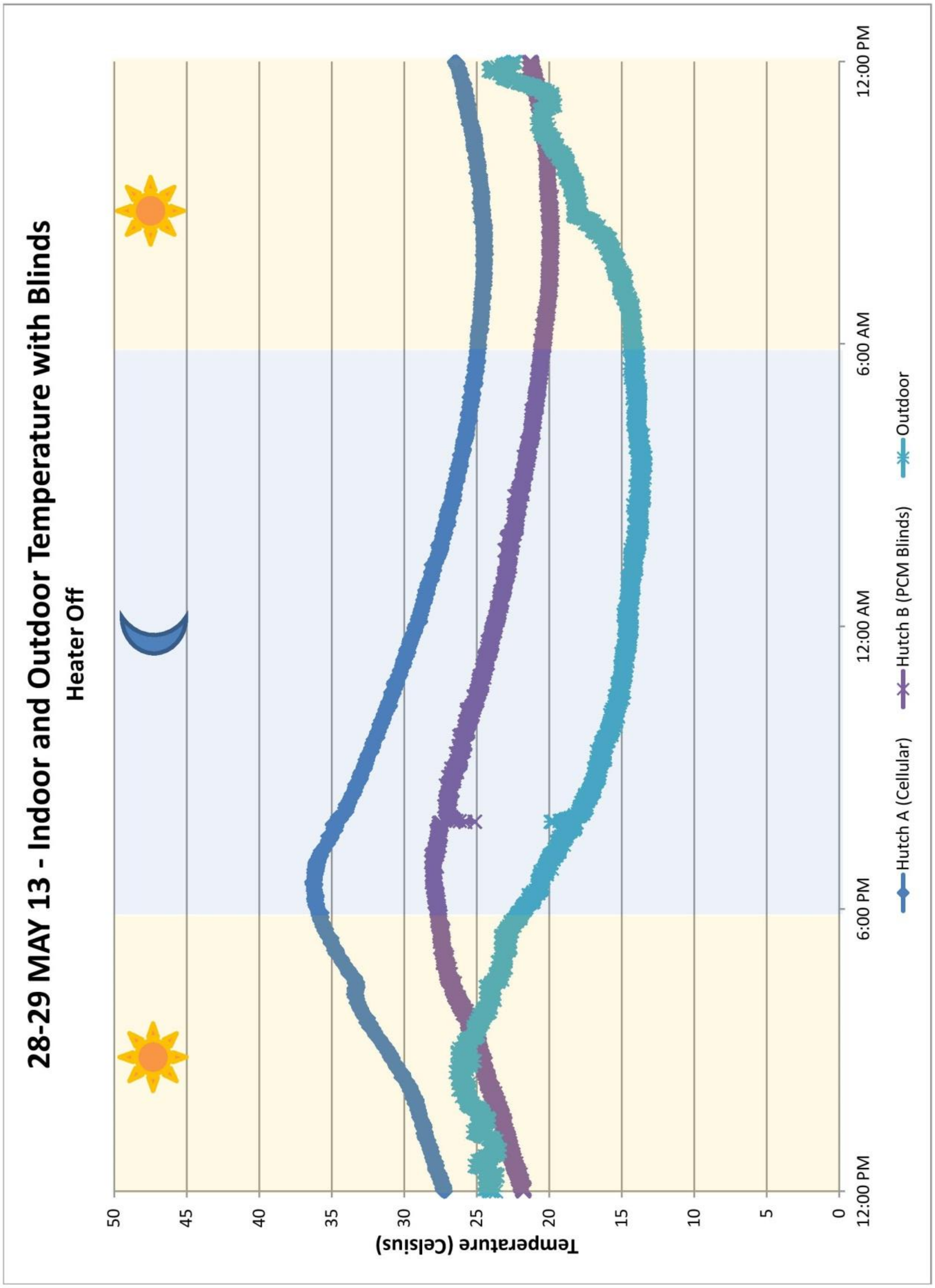

24-25 MAY 13 - Indoor and Outdoor Temperature with Nothing
Heater Off
Temperature (Celsius)
50
45
40
35
30
25
20
15
10
5
0
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch A
Outdoor
Hutch B


25-26 MAY 13 - Indoor and Outdoor Temperature with Blinds
Heater Off
Temperature (Celsius)
50
45
40
35
30
25
20
15
10
5
0
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Outdoor
Hutch B (PCM Blinds)

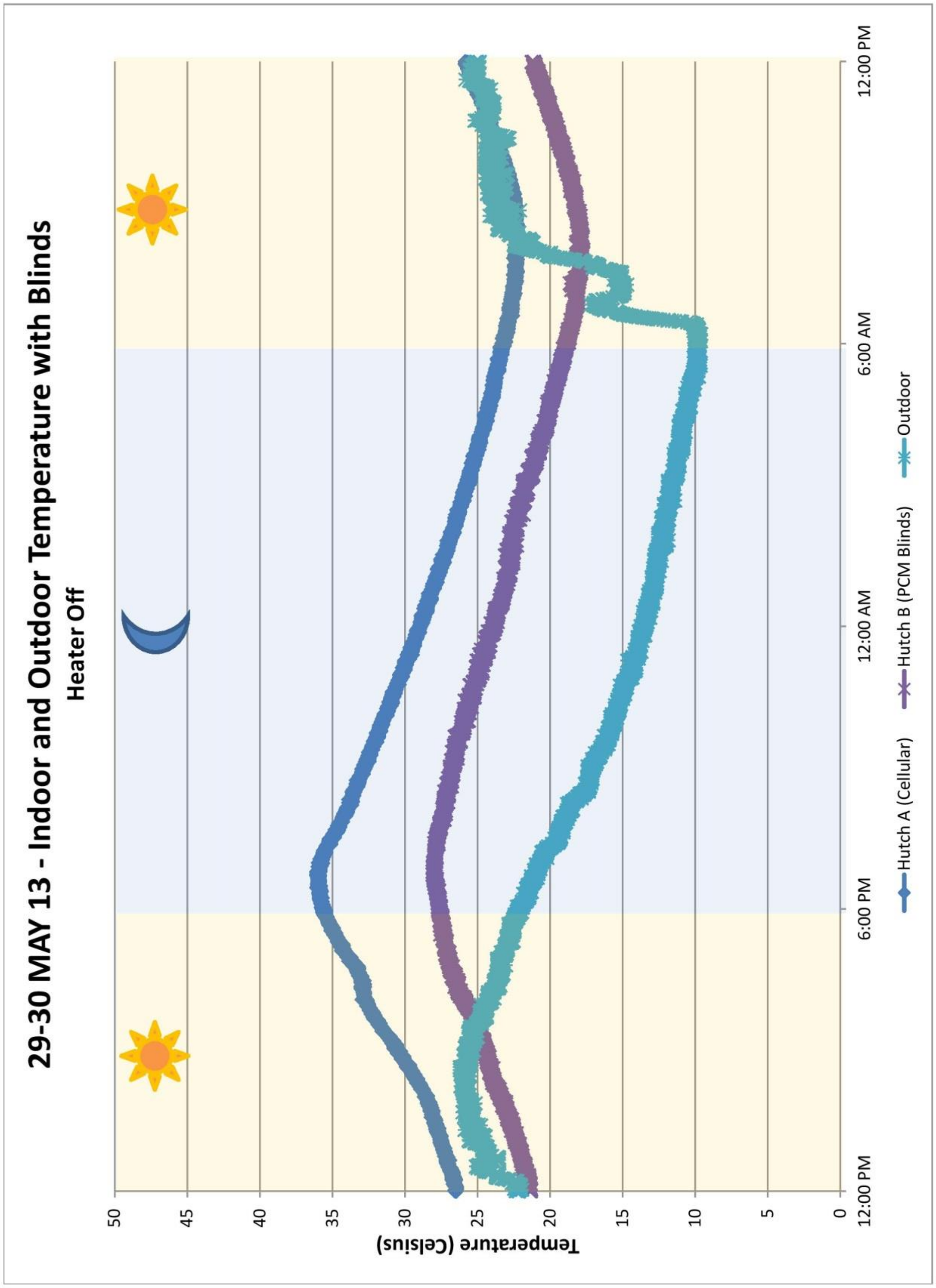

26-27 MAY 13 - Indoor and Outdoor Temperature with Blinds
Heater Off
Temperature (Celsius)
0
5
10
15
20
25
30
35
40
45
50
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Outdoor
Hutch B (PCM Blinds)



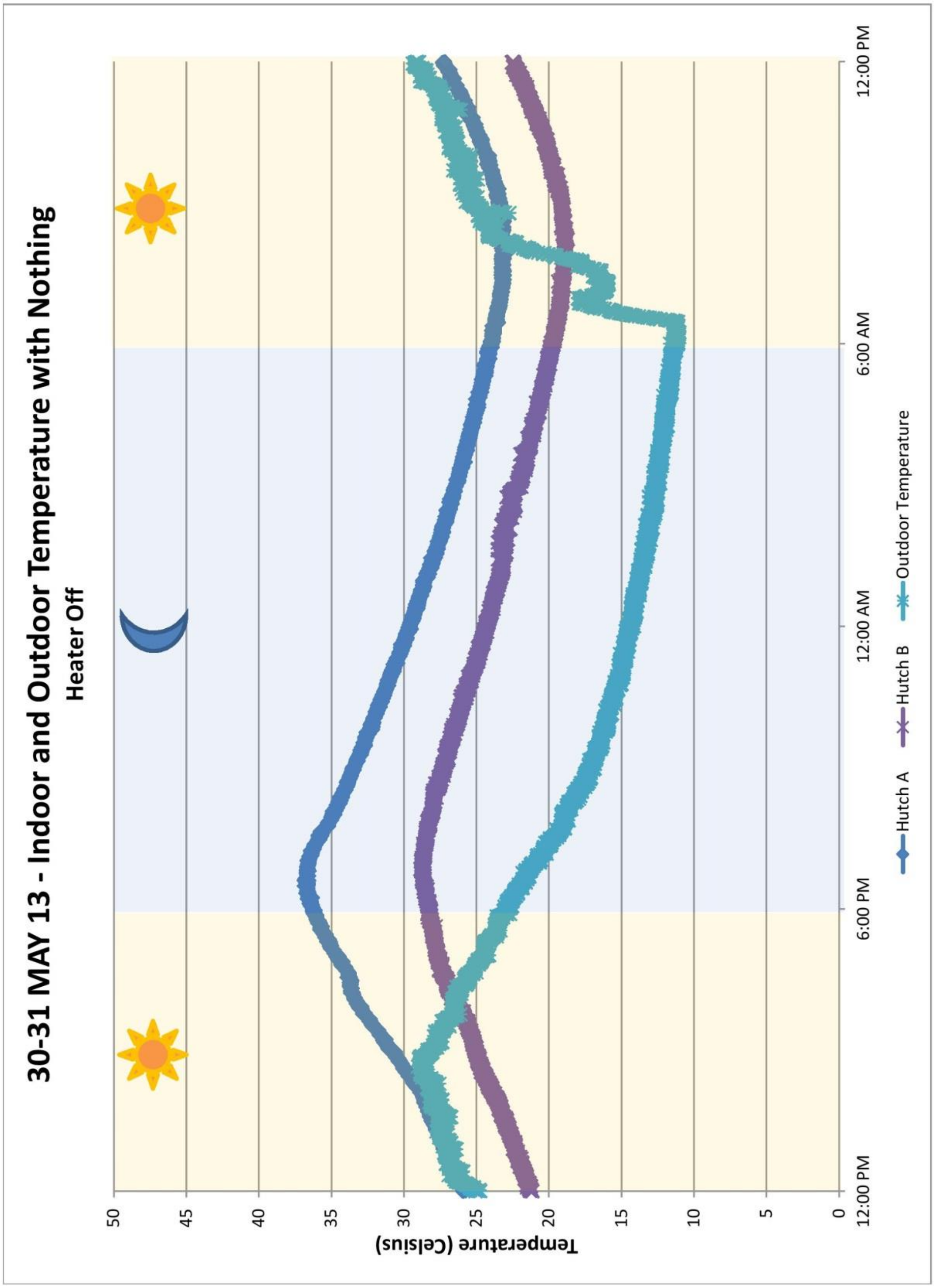
27-28 MAY 13 - Indoor and Outdoor Temperature with Blinds
Heater Off
Temperature (Celsius)
0
5
10
15
20
25
30
35
40
45
50
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch A (Cellular)
Hutch A (PCM Blinds)
Outdoor



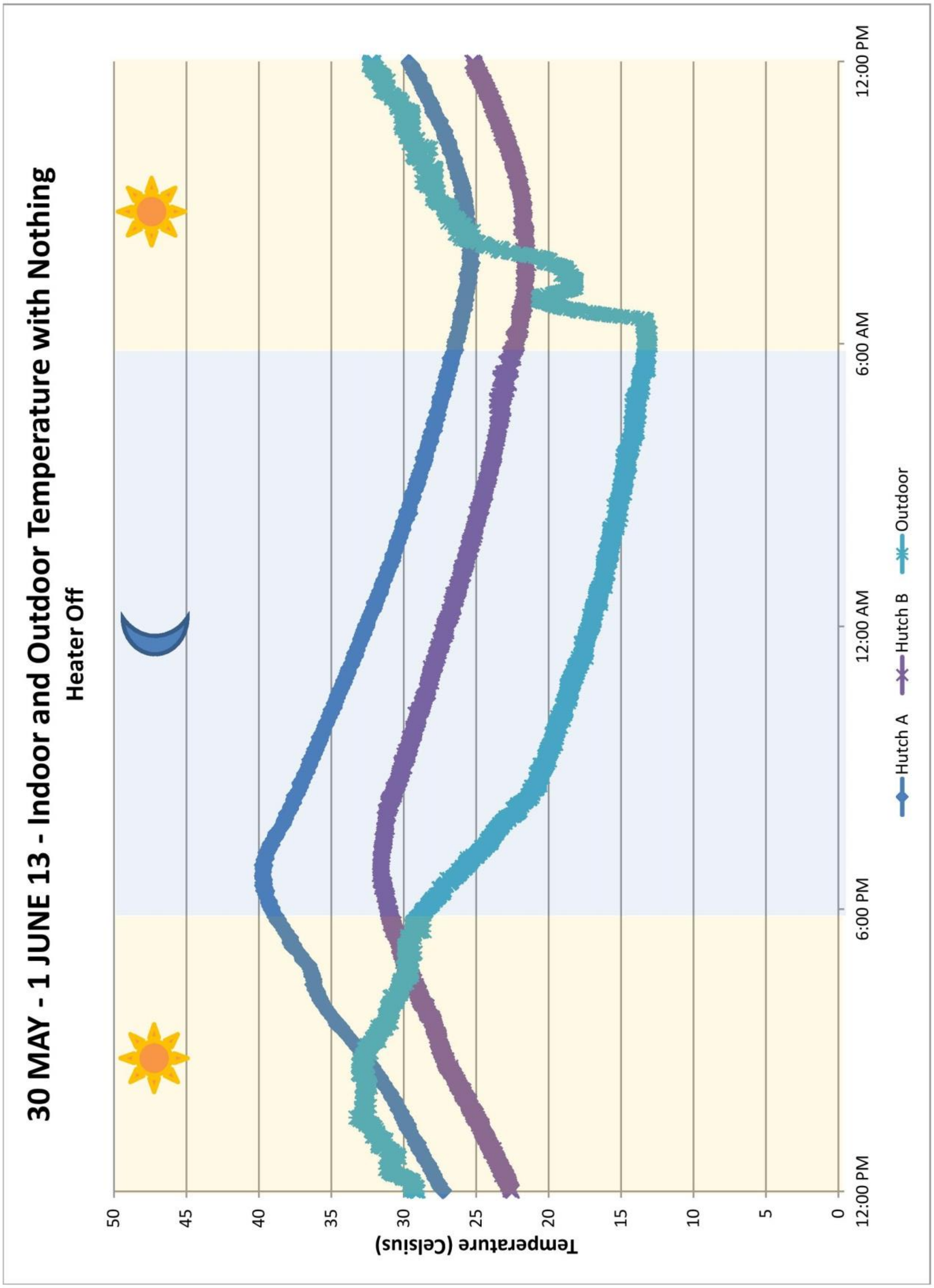
28-29 MAY 13 - Indoor and Outdoor Temperature with Blinds
Heater Off
Temperature (Celsius)
0
5
10
15
20
25
30
35
40
45
50
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch A (Cellular)
Hutch B (PCM Blinds)
Outdoor



29-30 MAY 13 - Indoor and Outdoor Temperature with Blinds
Heater Off
Temperature (Celsius)
0
5
10
15
20
25
30
35
40
45
50
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch A (Cellular)
Hutch B (PCM Blinds)
Outdoor



30-31 MAY 13 - Indoor and Outdoor Temperature with Nothing
Heater Off
Temperature (Celsius)
0
5
10
15
20
25
30
35
40
45
50
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch A
Hutch B
Outdoor Temperature


30 MAY - 1 JUNE 13 - Indoor and Outdoor Temperature with Nothing
Heater Off
Temperature (Celsius)
50
45
40
35
30
25
20
15
10
5
0
12:00 PM
6:00 PM
12:00 AM
6:00 AM
12:00 PM
Hutch A
Hutch B
Outdoor

Data collected for melting and solidification of louvers during California Spring. The start time for melting was sunrise (7:00 AM) and the start time for solidification was sunset (7:00 PM)

Trial	Date	Quarter-Cut		Half-Cut	
		Melt	Solidify	Melt	Solidify
1	March 1-3	~4.0 Hours	~8.0 Hours	~6.5 Hours	~12 Hours
2	March 3-5	~5.0 Hours	~8.0 Hours	~6.5 Hours	Not Solidified
3	March 7-9	~5.0 Hours	~8.0 Hours	~5 Hours	Not Solidified
4	March 11-15	~4.5 Hours	~8.0 Hours	~5.5 Hours	Not Solidified
Average		4.625 Hours	8.0 Hours	5.875 Hours	12+ Hours

Appendix A.12: Lawrence Berkely National Laboratory Grant Proposal and Requirements

Max Tech and Beyond

Appliance Design Competition 2013

Lawrence Berkeley Nation Laboratory

Phase Change Material in Automated Window Shades

End Use(s): Daytime insulation and nighttime space heating

Lead Advisor: Hohyun Lee, Assistant Professor (Curriculum Vitae attached)

Department: Mechanical Engineering, Santa Clara University

Phone/email: 408.554.5283, hlee@scu.edu

Student Team: A team of 3-4 students, including:

Quinlan Adler (Lead), senior Mechanical Engineer

quinadler@gmail.com; 425.443.0075

Jake Gallau, senior Mechanical Engineer

jgallau@gmail.com; 408.806.9392

Ali Nash, senior Mechanical Engineer

alinicolenash@gmail.com; 408.406.7880

Potential for one additional senior Mechanical Engineer

Undergraduate ☒ Graduate ☐ Both ☐ Senior Design course ☒ Other ☐

Industry Partner and Contribution: N/A

Percent per unit energy savings over current best-on-market products:

- 100% improvement in space heating capacity over traditional window shades

- 45% reduction in overall space heating energy usage

Table 1: Estimated national energy savings potential in quads per year

A	End uses to which the prototype applies	Space heating
B	Annual energy consumption of the end uses	6.15 quadrillion BTUs[18]
C	Fraction of the end uses to which the prototype innovation applies	45%
D	Estimated per unit energy savings with respect to average product on the market	100% over traditional blinds
E	Estimated annual energy savings	2.77 quadrillion BTUs

[18] http://buildingsdatabook.eren.doe.gov/tableview.aspx?table=2.1.5

Proposal Narrative

Although the direct use of solar thermal energy is an efficient way to provide domestic hot water and space heating, the energy demand is higher when the solar energy is not available. To store thermal energy for later use, thermal energy storage (TES) devices are necessary. To date, TES technologies have primarily been developed to use phase change materials (PCMs), either as simple thermal mass or in complicated systems in which the PCM is pumped through the structure. In each case, the final result has suffered from excessive ambient heat loss, or requiring an extreme amount of pumping power.

The proposed project will develop crescent-shaped louvers filled with a PCM that can be installed in front of or in between windows (Fig. 1). While the flat side of the louver will be made of a high emissivity material to effectively absorb and release solar energy, the rounded edge will be comprised of a reflective surface. During the day, the flat side of the blind will face outwards, keeping the interior cool. The heat from the sun will melt the enclosed PCM, yet will not permeate through the blind into the room because of the reflective, insulating surface. During the night, the blinds will be flipped so the flat edges face inside and release the latent heat indoors.

The PCM for this product is paraffin wax, due to its melting temperature of approximately 30 °C. Paraffin wax is noncorrosive, nontoxic, and cheap. However, its main drawback is its low thermal conductivity, approximately 0.25 W/m•K. Based on former nanosuspension studies,

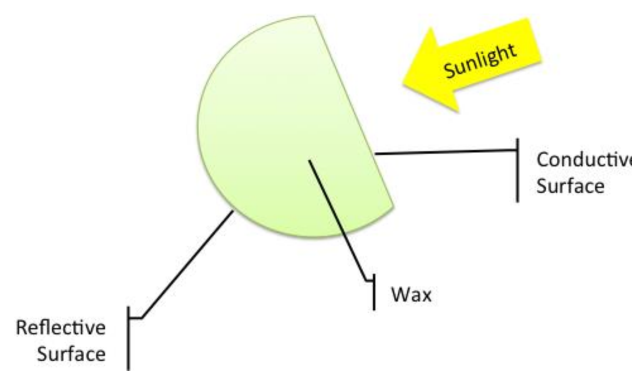


Figure 1: Louver System Cross-section (during the day)

thermal conductivity can be enhanced by adding highly conductive filler to the liquid wax[19,20,21]. For this project, multi-walled carbon nanotubes (MWNTs) will be utilized as the filler material. This will allow the wax composite to melt and solidify at a faster rate.

Additionally, a control system will be implemented to allow the blinds to switch position throughout the day, depending on the temperature and brightness of the outside environment. Once the sensors detect a significant drop in the ambient temperature and light, the louvers will automatically flip inward, beginning the solidification of the wax and the heating of the house. The control system will be comprised of a suite of sensors, including: temperature sensors, brightness sensors, and motion sensors. These three sensors will be programmed to work together to ensure that the available thermal energy is used to space heat the house in the most efficient manner. Last year, the PI received a grant from Max Tech and Beyond on an automated window blind control system to minimize energy consumption. The outcome of the project will be used toward this approach as well.

If the blinds perform as expected, they will be implemented in at least one west-facing window in Santa Clara University's 2013 Solar Decathlon House. The house, which will be showcased in Irvine, CA, in mid-October of 2013, will be judged for its energy saving capabilities, as well as the ingenuity of its mechanical systems.

Energy savings potential

Given the expected dimensions of each louver (36'' long, 1'' wide, ~0.25'' thick), about nine cubic inches of volume are available to store the PCM. Factoring in the fact that wax

[19] Sari, Ahmet. "Thermal conductivity and latent heat thermal energy storage characteristics of paraffin/expanded graphite composite as phase change material." Applied Thermal Engineering. 8 Nov 2006.
[20] Zhou, D. et al. "Review on thermal energy storage with phase change materials (PCMs) in building applications." Applied Energy. 15 Aug 2011.
[21] Zhou, D. and Zhao, C.Y. "Experimental investigations on heat transfer in phase change materials (PCMs) embedded in porous materials." Applied Thermal Engineering. 18 Nov 2010.

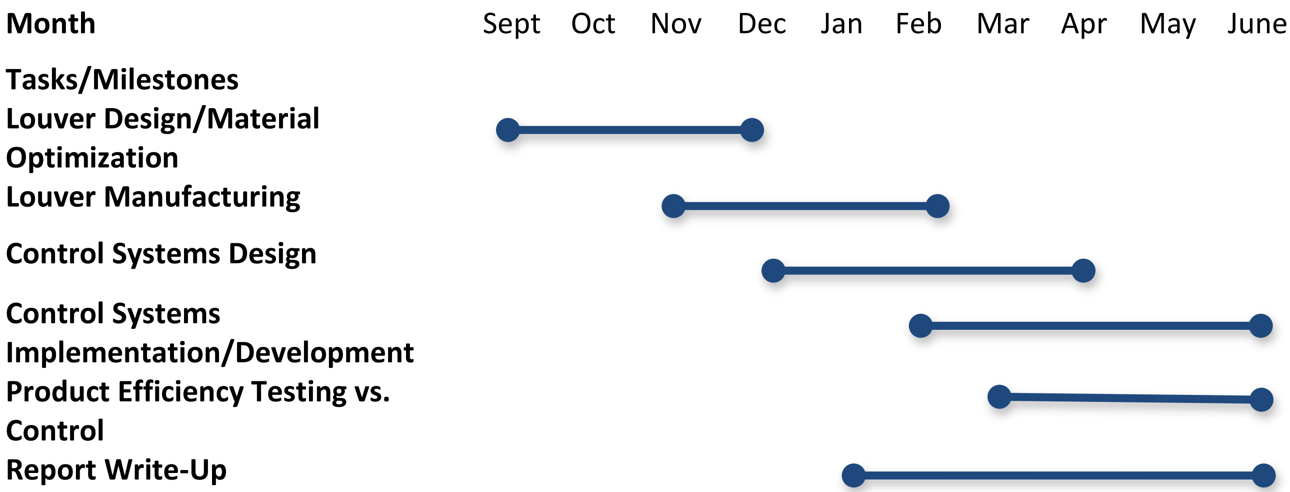
expands by approximately 10% when it melts, only 85% of the louver will be filled with solid wax. Knowing the latent heat of fusion of the wax is 180 kJ/kg, up to 20 kJ of energy per louver will be available. When suspended from a six-foot window, this equates to 72 louvers, or 1450 kJ, of usable thermal energy. This results in approximately 0.40 kWh of energy from a single window shade.

With the installation of automated window shades on five windows of equal size, it is estimated that energy usage could be cut by 45%, or 2.0 kWh per day. These values are dependent upon the number of blinds installed, but could plausibly rise enough to justify the complete disuse of traditional space heating technology. These benefits are of course in addition to the conventional space cooling benefits that the blinds provide. While the initial expenses of an automated window shade system will be higher than those of traditional manual, reflective window shades, the efficient operation of the system will offset the energy and operational costs of traditional space heating systems.

Educational Context

3-4 senior ME students will design and test the blind system; this will involve geometric analysis to determine the optimal shape and size of the louvers, as well as energy and heat transfer analyses to determine which materials should be used for the front and back of each louver. Once the blinds have been manufactured, the students will explore the control system. In order to quantify how much energy is truly being saved, testing and troubleshooting will constitute the last phase of the design process.

Table 2: Project Plan and Timeline



Cost Proposal

The bulk of the project budget, approximately $9000, will go towards hardware and software for prototyping. We are also requesting student wages for one graduate student and one undergraduate student to carry out in-depth study of energy conservation.

Table 3: Proposed Project Budget

<u>Salaries & Wages</u>	
Graduate student (1)	
12 weeks (Academic Year) x 20 hours/wk * $15/hr	$3,600.00
Undergraduate student (1)	
12 weeks (Academic Year) x 20 hours/wk * $10/hr	$2,400.00
Total Proposed Labor Cost	**$6,000.00**
<u>Benefits</u>	
Student AY @ .85%	$51.00
Total Benefits	**$51.00**
<u>Other Direct Costs</u>	
Paraffin wax (PCM) - 15 kilos	$750.00
Multi-walled carbon nanotubes (MWNTs) - 10 grams x 5	$1250.00
Blind materials (subtotal)	**$2,650.00**
Graphite (absorption material)	$100.00
Reflection material	$550.00
Misc. blind hardware	$2,000.00
Control system & electronic components	$2,000.00
Test Supplies	$500.00
Tax (8.75%) & shipping (approximate)	$1,500.00
Total Other Direct Costs	**$8,650.00**
<u>Total Direct Costs</u>	**$14,701.00**
Modified Total Direct Costs: Indirect Costs Base Value	$14,701.00
Indirect Costs (TDC*35.5%)	$5,219.00
Total Estimated Project Costs (MTDC indirect cost base value + indirect costs)	**$19,920.00**

MAXTECH AND BEYOND: APPLIANCE DESIGN COMPETITION (AY12/13)
Project Plan

Team Name: Molten Moon Mechanical

Project Name: Phase Change Material in Automated Window Shades

Faculty Lead: Dr. Hohyun Lee **Student Lead:** Quinlan Adler

Project Plan through January, 2013

Prepared By: Quinlan Adler, Jake Gallau, Alex Zatopa, and Ali Nash **Date:** November 10, 2012

BRIEF LIST OF PLANNED TASKS (October – January)

Task	Target Date	Status*
Project Definition and Specifications Report	October 9, 2012	X
Project Definition and Specifications Presentation	October 9, 2012	X
Customer Needs Assessment	October 15, 2012	X
Sun Sensor Study 1	October 25, 2012	X
Fall Prototype Systems Level SolidWorks Model	October 30, 2012	X
Fall Prototype Subsystems SolidWorks Models	October 15, 2012	X
Sun Sensor Study 2	November 5, 2012	X
MaxTech and Beyond Team Teleconference Call	November 16, 2012	X
Fall Prototype Manufacture and Completion	November 25, 2012	X
Purchase Prototype Materials	November 1, 2012	X
Complete Single Louver Prototype (1)	November 5, 2012	X
Waterproof Testing for Louver Prototype (1)	November 6, 2012	X
Complete Louver Prototype (2) Re-Build from Analysis Results	November 19, 2012	X
Waterproof Testing for Louver Prototype (2)	November 20, 2012	X
PCM Melting Tests - Evaluate Prototypes	November 20, 2012	X
Complete Control/Actuation System for Single Louver	November 25, 2012	X
Formal Conceptual Design Presentation for Outside Judges	November 27, 2012	X
Conceptual Design Report	December 1, 2012	X
Submit Max Tech and Beyond Team Photos and Website Team Info	December 3, 2012	X
Sun Sensor Study 3	December 10,	X

	2012	
MaxTech and Beyond Status Report 1	February 11, 2013	**X**

*Blank box for incomplete tasks, and **X** for completed tasks.

Weekly Team Meetings:**

Team + Advisor – Mondays from 11:45 to 1:00 PM.
Team – Mondays from 5:00 to 7:00 PM.
Team – Fridays from 11:45 to 1:00 PM.
**These are mandatory scheduled meetings each week. Other meeting times may be scheduled to complete tasks.

BRIEF LIST OF EXPECTED MILESTONES

Milestone	**Target Date**
Fall Prototype Manufacture and Completion	November 25, 2012
Conceptual Design Report Presentation and	November 27, 2012
Report	December 1, 2012
Fall Prototype Testing	December 20, 2012
Analysis of Results and Final Prototype	January 2013
Kick-Off of Final Design	January 2013

Notes:

- Tasks generally help define and drive the progress of a project. A new project is always divided into tasks and based on the resources available. They can range in size. Examples of tasks may be making substantial purchases, submitting requested information to LBNL, attending meetings or meeting with potential sponsors or other expertise.
- Milestones have more visibility than tasks. They usually comprise several completed tasks. Examples of Milestones may be the final team selection with an initial kick-off meeting or the sign off on a final design.

Status Report #1

Prepared By: Quinlan Adler, Jake Gallau, Alex Zatopa, and Ali Nash   Date: February 6, 2013

LIST TEAM ACCOMPLISHMENTS (completed planned tasks and updated/additional tasks completed):

Formal Conceptual Design Presentation for Outside Judges
Conceptual Design Report
Version 01 SolidWorks Component and Assembly Drawings for Final System
Temperature, Luminosity, and Energy Consumption Tests Performed on Hutches (Testing Environment)
Tests + Comparison of PCMs: Made Decision on PCM for Final System
Estimated Required Amount + Purchased PCM for Final System
Finalized Louver Manufacturing Process + Optimized Design (Size, Shape, Aesthetics)
Wrote and implemented code with Actuation System to orient louver towards the sun with preset azimuthal angle obtained from historical weather data for the same location, date and time.
Single Louver System Prototype + Preliminary Testing

Weekly Team Meetings:**
Team + Advisor – Mondays from 11:45 to 1:00 PM.
Team – Mondays from 5:00 to 7:00 PM.
Team – Fridays from 11:45 to 1:00 PM.
**These are mandatory scheduled meetings each week. Other meeting times may be scheduled to complete tasks.

PLEASE INDICATE THE STATUS OF YOUR PLANNED MILESTONES LISTED ABOVE:

Milestone	Target Date	Actual Date	Comments
Fall Prototype Manufacture and Completion	November 25, 2012	January 15, 2013	Complete: Lead times on components and failures with Versions of Sub-Assemblies increased completion date.
Conceptual Design Report Presentation and Report	November 27, 2012 December 1, 2012	November 27, 2012 December 1, 2012	Complete: On Time.
Kick-Off of Final Design	January 2013	January 2013	Complete: Final design has already begun but the final design will not be confirmed until completion of prototype testing and analysis.

PLANNED TASKS or MILESTONES NOT YET COMPLETED

PLANNED TASK	REASON FOR DELAY	NEW TARGET DATE
Fall Prototype Testing	In Process: Prototype is complete and testing is currently in process. Due to lead-time of fall prototype manufacture.	Jan/Feb 2013
Analysis of Results	In Process: Analysis is being done in parallel with prototype testing. Due to lead-time of fall prototype manufacture.	February 2013

BUDGET

INITIAL BUDGET (LBNL FUNDING)	TOTAL INVOICED	SPENT, NOT INVOICED YET
$592.36	$14,407.64	$152.29

BUDGET – PLEASE NOTE ANY ADDITIONAL INFORMATION IF NECESSARY: N/A

ADDITIONAL INFORMATION

No changes in team status, the team consists of the same members and faculty advisor.

PROVIDE A BRIEF LIST OF PLANNED TASKS for remainder of the academic year:

Task	Target Date
Fall Prototype Testing	February 1, 2013
Customer Assessment Study - Feedback on Aesthetics/Operation of Fall Prototype for Final System	March 2013
Fall Prototype Test Results Analysis	February/March 2013
Final Prototype Design and Drawings	February/March 2013
SCU Testing Analysis Report	February 25, 2013
SCU Project Update	March 15, 2013
Write Code for Solar Tracker	April 2013
Temperature, Luminosity, Energy Consumption Studies in Hutches	February – April 2013
SCU Preview Days	March 12 and 13, 2013
Purchase Final Assembly Components	February 2013
Begin Manufacture of Custom Components	March 2013
Welded Assembly Frame	March 30, 2013
Louver Set	March 15, 2013
Fill Louver with FCM	March 30, 2013
Assemble Final System	March/April 2013

MaxTech and Beyond Status Report 2	April 2013
Test Final Blind System	April 2013
Analysis of Test Results	April 2013

PROVIDE A BRIEF LIST OF EXPECTED MILESTONES for the remainder of the academic year.

Task	**Target Date**
SCU Senior Design Conference	May 9, 2013
Submit MaxTech Webinar Slides	May 2013
MaxTech Webinar	May 23, 2013
MaxTech Preliminary Report Outline	June 17, 2013
MaxTech Final Team Report	June 28, 2013
SCU Senior Design Product Report	June 2013

Notes:

- Tasks generally help define and drive the progress of a project. A new project is always divided into tasks and based on the resources available. They can range in size. Examples of tasks may be making substantial purchases, submitting requested information to LBNL, attending meetings or meeting with potential sponsors or other expertise.
- Milestones have more visibility than tasks. They usually comprise several completed tasks. Examples of Milestones may be the final team selection with an initial kick-off meeting or the sign off on a final design.

Status Report #2

Team Name: Molten Moon Mechanical

BUDGET

INITIAL BUDGET (LBNL FUNDING)	**TOTAL INVOICED**	**SPENT, NOT INVOICED YET**
$15,000.00	$1,532.67	Approximately $1500.00

BUDGET – PLEASE NOTE ANY ADDITIONAL INFORMATION IF NECESSARY: N/A

ADDITIONAL INFORMATION

No changes in team status, the team consists of the same members and faculty advisor.

Please include any other pertinent information below for this final status report:

- All raw materials have been purchased for the final product and assembly will be completed over the course of two weeks.
- Protoype testing continues until the final assembly is built and we have concrete results.
- Decided to go with Quarter Louver rather than Half Louver for Final Assembly since it completely melts and solidifies in most weather conditions, whereas the Half does not.
- We will be purchasing all the final electronics and parts over the next few weeks to complete our final assembly to have some testing done prior to Santa Clara University Senior Design Competition on May 9, 2013.

Appendix A.13: Center for Science, Technology, and Society Grant Proposal and Requirements

Roelandts Grant - Student Application
Basic Information
*Please limit your response to 100 words or less for placement on our website.

Title*
Phase Change Material in Automated Window Shades

Description of Project*

The goal of this proposal is to develop window blinds filled with phase change material to store the sun's energy and heat a home at night, while shading and keeping it cool during the day. This will be done by changing the position of a thermally absorptive edge throughout the day, depending on the temperature, and brightness of the sun. The proposed project will provide an economic and sustainable way to shade and heat a home, as well as provide new innovations in solar technology and thermal storage to be utilized around the world.

Principle Investigator Name: Jake Gallau
Resume 1*
Transcript 1*

Co-investigator Name: Quinlan Adler
Resume 2*
Transcript 2*

Co-investigator Name: Alex Zatopa
Resume 3*
Transcript 3*

Co-investigator Name: Ali Nash
Resume 4*
Transcript 4*

Co-investigator Name: N/A
Resume 5* N/A
Transcript 5* N/A
*File must be less than 1500k, and of the type: **doc, docx, pdf, rte, txt, and wpd.**

Please answer the following questions. If you have any questions you can contact Adelene Gallego Ramos at AGallegoramos@scu.edu.

Section 1: Problem Definition

Provide a clear definition of the social, environmental, or technological problem you intend to research.
This should clearly explain how your research project will promote the use of science and technology to benefit underserved populations worldwide.

The backbone of our project is to develop a hardy and simple solution to the hot days and extremely cold nights of Northern Africa that does not require infrastructure or education to understand and operate. By simply providing the citizens of the Northern African region with a technology that absorbs the sun's daytime energy and, with the pull of a simple switch, turns to release that energy at night, we hope to provide improved comfort and health to underserved populations.

Thermal mass is in fact an age old technology that has been utilized since the very first structures were built, and as such is already utilized and understood in much of the world. We simply hope to improve and augment the capabilities of the existing thermal energy storage systems by introducing both phase change and an element of user controllability. Ultimately, our product will provide an economic and sustainable energy source for the world and could potentially be optimized for a variety of weather conditions.

What is the social benefit outcome that this research might support?*
This project can provide benefits to anyone at all with need for nighttime heating of their residential space; however, by working to keep the cost of the final product low, and by optimizing the design for the locals with hot, sunny days and cool nights, such as Northern Africa, we hope to provide a cheap, alternative to wood-burning fireplaces or inefficient electric space heaters. Additionally, the saved energy that these louvers offer can be earmarked to other more pressing energy concerns, such as water heating. We hope that the research and product design may also stem product and technological development to further improve health and quality of life by reducing energy consumption.

Who might directly or indirectly benefit from this line of research?*
In its simplest form, this project should produce a significant development in domestic space heating. This cheap, efficient method could benefit people in tropical and temperate regions across the world. Through several programs including Santa Clara's Frugal Innovations Lab, and EWB (Engineers Without Borders), we expect to be able to spread any developments made and perhaps several working copies of our design to communities in South America. In addition, if product development proceeds as planned, the blinds will be showcased in the Santa Clara's 2013 Solar Decathlon house, and seen by hundreds of thousands of visitors.

Section 2: Research Plan

Research Plan*

Provide a research plan, preferably including materials and methods. Justify this with published literature, if possible. Describe what you propose to do, who you will do it with, where and when.

The proposed project is to develop PCM-filled crescent-shaped louvers to replace traditional window blinds. The window shading system will be installed indoors and in front of windows, or potentially in-between glass panes. A cross-section of the basic louver prototype is shown in Figure 1. One key phase of the project is deciding which material to use for each aspect of the design. The flat side of the louver will be made of a highly emissive material to effectively absorb and release solar energy. A black body, or material that will ideally absorb all electromagnetic radiation obtained from natural sunlight, has potential to be implemented—graphite-coated glass and acrylic are the two most reliable options at this point in time. The elliptic back-edge of the louver will be comprised of a reflective and insulating surface to avoid heat loss through this specific material. During the day, the flat side of the blind will face outwards, keeping the interior cool. The heat from the sun will melt the enclosed PCM, yet will not permeate through the blind into the room because of the reflective, insulating surface. During the night, the blinds will be flipped so the flat edges face inside and release the latent heat indoors. The PCM selected for utilization in the system design is paraffin wax, due to its beneficial low melting temperature of approximately 30°C. Other benefits of paraffin wax also include that it is a noncorrosive, non-toxic, and inexpensive material.

The design will also consist of a control system that will operate the blinds so that they switch position throughout the day, depending on the temperature, and brightness of the sun. With the use of temperature, brightness, and motion sensors, upon detection of a significant drop in the ambient temperature and light, the louvers will automatically flip inward, thus beginning the solidification of the wax and the heating of the house. The three sensors will be programmed to work together to ensure that the available thermal energy is used to space heat the house in the most efficient manner. A basic diagram of control system setup is shown in Figure 2.

The proposed crescent louver design will be optimized so that each blind has a large conductive surface to absorb large quantities of sunlight, as well as a thick reflective surface for high quantities of paraffin wax to be stored. The louvers must also be aesthetically pleasing while maintaining relatively cheap material costs. The preliminary dimensions of each louver will be approximately 84.0 inches long, 5.0 inches wide, and 1.0 inch thick, which allows for 420 cubic inches of volume available to store the PCM per louver. The paraffin wax expands by approximately 10% when it melts, so only 85% of the louver will be filled with solid wax. Through previous study, the latent heat of fusion of the wax was approximated to be 180 kJ/kg, which will allow for up to 58.9 kJ of available latent energy to be stored per louver.

If the blinds perform as expected, they will be implemented in a 3-foot by 7-foot west-facing window in Santa Clara University's Solar Decathlon House in October of 2013. This equates to an approximate need of 7 louvers, and will produce 412.7 kJ of usable thermal energy. This results in approximately 0.1146 kWh of energy from the window shades. With the installation of the current automated window shades design in the bedroom of the Solar House, it is estimated that energy usage could be cut by 50%, or 1.015 kWh of the average 1.889 kWh heating load lost per 6-hour span of night. These values are dependent upon the size and number of blinds installed, but could plausibly raise enough to justify the complete disuse of traditional space heating technology. These benefits are of course in addition to the conventional space cooling benefits that the blinds provide. While the initial expenses of an automated window shade system will be higher than those of traditional manual, reflective window shades, the efficient operation of the system will offset the energy and operational costs of traditional space heating systems.

References

Rubitherm Technologies GmbH. "PCM's in Thermal Energy Storage Applications." Rubitherm Phase Change Material. www.rubitherm.de/english/index.htm

Sari, Ahmet. "Thermal conductivity and latent heat thermal energy storage characteristics of paraffin/expanded graphite composite as phase change material." Applied Thermal Engineering. 8 Nov 2006.

Zhou, D. et al. “Review on thermal energy storage with phase change materials (PCMs) in building applications.” Applied Energy. 15 Aug 2011.

Zhou, D. and Zhao, C.Y. “Experimental investigations on heat transfer in phase change materials (PCMs) embedded in porous materials.” Applied Thermal Engineering. 18 Nov 2010.

Timeline

This grant is for a period of 18 months for faculty and 7 months for student investigators. Please provide a timeline of your research over the designated period.

Over the course of the academic year and prior to the SCU Senior Design Competition in May. the 7-month period of the Roelandt Grant would aid in the funding of the following tasks and milestones our group plans to accomplish.

Blind Louver Design/Size and Shape Optimization: September - October 2012
Window Shade Initial Prototype Manufacturing: November – December 2012
Blind Prototype Experimentation: December – February 2012
Control Systems Design: December – April 2012
Experimentation Analysis and Design Re-Evaluation: January – February 2012
Window Shade Final Prototype Manufacturing: February – March 2012
Final Product Efficiency Testing: March – June 2012
Final Report Write-Up: January – June 2012

Budget

Please provide an itemized budget projection for any expenses your plan to charge to this grant fund. International travel is eligible for funding, but requires clear justification.
Our team has submitted proposals for grants to cover the expenses outlined in the table below. The bulk of the project budget will go towards hardware and software for the design project. The current proposed plan is that the income for product integration into the Solar Decathlon House, approximately $8000, will be funded by a grant from the Lawrence Berkeley Nation Laboratory (LBNL). The Fall Quarter Prototype, approximately $3250, will be partially covered by a grant from the Center for Science, Technology and Society (CSTS). If any of the proposals are not accepted or cannot fulfill the budget, we are proposing for the entire budget to be funded by the Santa Clara School of Engineering. If LBNL and CSTS accept our proposals, our team is requesting the Dean’s Office to cover the cost of the first prototype and remaining of the second window shade prototype, approximately $1000.

Proposed Expenses
First Louver Prototypes (Subtotal) $230.00
PVC + Foil/Metallic $50.00
(Reflective Material)
Acrylic + Graphite Paint (Absorption Material) $50.00
Misc. Blind Hardware $100.00
CA Sales Tax (7.25%) & Shipping (Approximate) $30.00

Second Window Shade Prototype (Subtotal) $3,220.00
Paraffin Wax (PCM) – 5 kilos $250.00
Blind Materials
Reflective Material $550.00
Absorption Material $100.00
Misc. Blind Hardware $400.00
Control System & Electronic Components $1,000.00
Test Supplies $500.00
CA Sales Tax (7.25%) & Shipping (Approximate) $420.00

Solar Decathlon Integration (Subtotal) $7,820.00
Paraffin Wax (PCM) - 15 kilos $750.00
Multi-Walled Carbon Nanotubes (MWNTs) - 10 grams x 5 $1,250.00
Blind Materials
Reflective Material $550.00
Absorption Material $250.00
Misc. Blind Hardware $2,000.00
Control System & Electronic Components $2,000.00
CA Sales Tax (7.25%) & Shipping (Approximate) $1,020.00

Total Estimated Project Cost $11,270.00

Describe clearly to non-specialists the technologies or science you are investigating.
In essence, the goal of this project is to reinvent space heating in a way that provides a product capable of providing residential nighttime space heating without the need for electricity or fuel of any kind. Paraffin wax with a low melting temperature will be used in window shades to store the heat from the day and, with the flip of a switch just before bed, will rotate the blinds inward, and release the heat into the interior space. Past technologies have sought to accomplish similar ends, but have been crippled by their lack of flexibility and efficiency.

What social, cultural, or economic dimensions to the issue shape the application of science and technology for social benefit?*
Accessibility to clean, healthy, inexpensive, and efficient space heating is severely limited in most of the world. By providing a simple to use and inexpensive product that can either be controlled automatically, or can be scaled down for operation by a resident and without the consumption of electricity, we believe we can provide this much needed and long overdue access. The region of the world that we are targeting for use of our product, Northern Africa, has recognized the value of thermal mass for centuries, but this project will represent a significant advance in thermal energy storage technology.

What is novel and/or creative in your approach to investigating the issue?*
Our project includes two innovations to thermal mass that have been widely overlooked but will significantly augment the efficiency of the thermal mass. First is the inclusion of both a thermally absorptive and a thermal insulating face to our thermal mass. Previous technologies, such as Trombe walls, allow the energy to seep out both sides of the wall, losing half of the energy that was stored in the PCM to the environment. Our project protects against this by insulating the back edge of the thermal mass, thus, streamlining the energy flow into the interior space.

This innovation would not be possible without the inclusion of the second innovation which is the aspect of user controllability. By allowing the homeowner to adjust the angle of the blinds, the blinds can be directed to face the sun at any time of the day, achieving the maximum amount of energy storage, and then turned inward at night, to release 100% of that energy into the interior space.

Section 3: Disseminating Results
*Please limit your response to 100 words or less for placement on our website.

Describe how results are to be reported and to whom.*
As an undergraduate senior design project, we would have direct oversight from Dr. Hohyun Lee, a faculty adviser. Dr. Lee will appraise our work on a weekly basis and continue to drive us and the product development to its full potential. A completed senior design project is a requirement for graduation, and the added expectation of a completed product for use in the 2013 Solar Decathlon entry will ensure that any goals suggested by Dr. Lee are met.

Please describe an arena for public presentation or dissemination that would be appropriate for your research (e.g. professional conference, publication, SCU event). Do you believe you will be able to present your work in such an arena? Why or why not?*
As was noted earlier, the product will be showcased both in the 2013 Solar Decathlon, as well as in several venues as a completed senior design project. We will be expected to disseminate information on our product to uninformed public spectators at the Decathlon, as well as a room full of students and industry experts as part of our senior design process, and expect to be able to share our advances to both.

Why would a scholar studying in your research area, or in the area of social benefit, be interested in your research?*

With a focus on individuals and organizations with interests in thermal studies and the depletion of energy usage, our research would interest industry and technical experts with the development of a product that aids in improving current thermal energy storage struggles. This report also has an opportunity to educate our peers and future undergraduate engineer design teams. They could potentially be interested in determining how our final project design may be optimized to produce an even more energy efficient product.

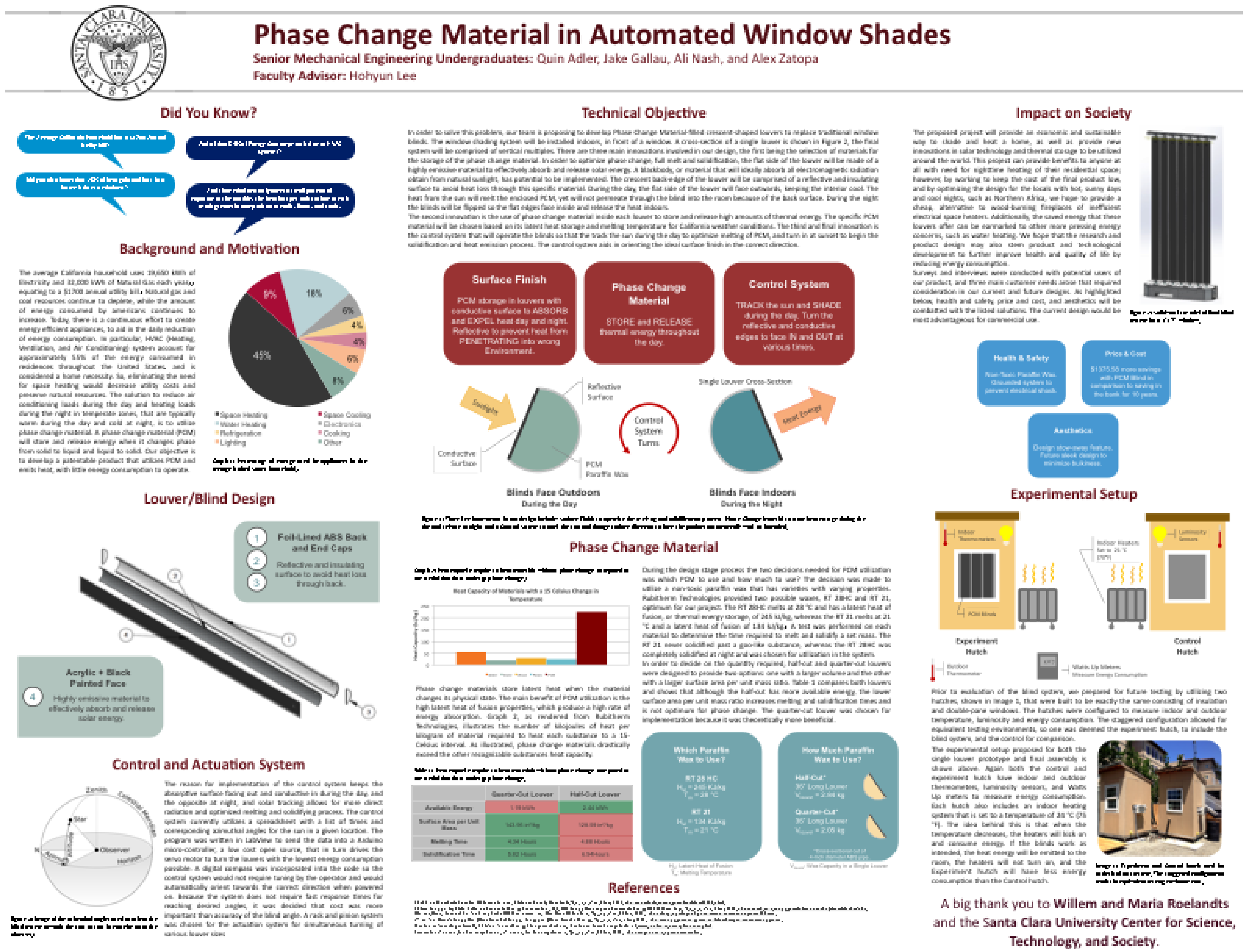
Section 4: Evidence of Faculty Supervision
*Please limit your response to 100 words or less for placement on our website.

Who is your faculty advisor?* Dr. Hohyun Lee

What role will the faculty member have in this project?*

As project advisor, Dr. Lee's role is to lead the direction of our group, ensure the quality of our work, and eventually, give final approval on our design. Important deliverables have been completed and continue to be set with his expertise in the product development process in the field of thermal studies. As the source of the inspiration for the project itself, he has a personal interest to aid our team in producing the most energy efficient and operational product. As experimentation and re-evaluation continues, we believe he will provide us with knowledgeable approaches to solve any current problem.

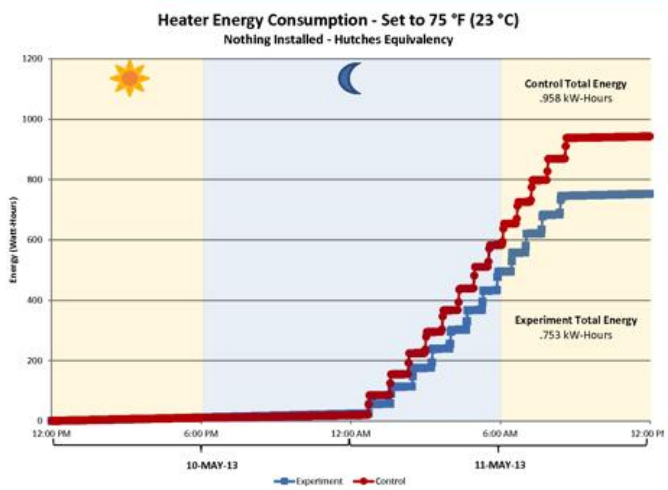
Letter of Faculty Support*
**Please provide a Letter of support from faculty member(s) overseeing the research project.*
Request from Dr. Lee with CSTS Proposal Draft.

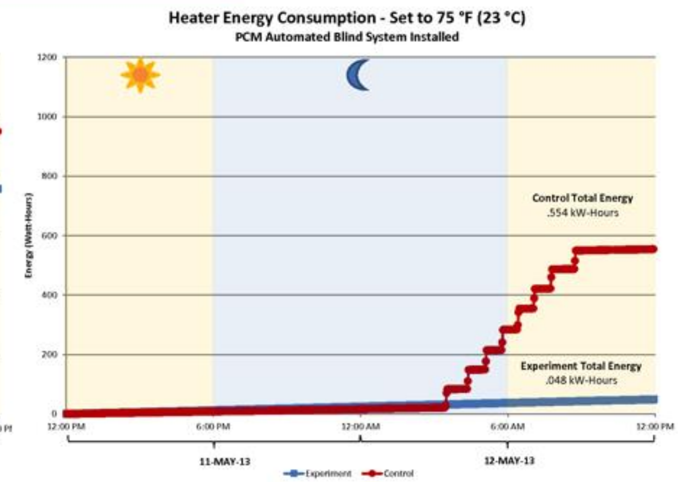

Phase Change Material in Automated Window Shades
Senior Mechanical Engineering Undergraduates: Quin Adler, Jake Gallau, Ali Nash, and Alex Zatopa
Faculty Advisor: Hohyun Lee
Did You Know?
Background and Motivation
45%
18%
6%
4%
4%
6%
8%
9%
Space Heating
Water Heating
Refrigeration
Lighting
Space Cooling
Electronics
Cooking
Other
Louver/Blind Design
Foil-Lined ABS Back and End Caps
Reflective and insulating surface to avoid heat loss through back.
Acrylic + Black Painted Face
Highly emissive material to effectively absorb and release solar energy.
Control and Actuation System
Zenith
Celestial Meridian
Star
Observer
Horizon
Technical Objective
Surface Finish
PCM storage in louvers with conductive surface to ABSORB and EXPEL heat day and night. Reflective to prevent heat from PENETRATING into wrong Environment.
Phase Change Material
STORE and RELEASE thermal energy throughout the day.
Control System
TRACK the sun and SHADE during the day. Turn the reflective and conductive edges to face IN and OUT at various times.
Sunlight
Reflective Surface
Conductive Surface
PCM Paraffin Wax
Control System Turns
Single Louver Cross-Section
Heat Energy
Blinds Face Outdoors
During the Day
Blinds Face Indoors
During the Night
Phase Change Material
Quarter-Cut Louver
Half-Cut Louver
Available Energy
Surface Area per Unit Mass
Melting Time
Solidification Time
Which Paraffin Wax to Use?
RT 28 HC
RT 21
How Much Paraffin Wax to Use?
Half-Cut
Quarter-Cut
References
Impact on Society
Health & Safety
Price & Cost
Aesthetics
Experimental Setup
Experiment Hutch
Control Hutch
A big thank you to Willem and Maria Roelandts and the Santa Clara University Center for Science, Technology, and Society.

Date	Installation	Control Energy Consumption	Experiment Energy Consumption	Experiment Percent Energy Consumption Decrease	Maximum Outdoor Temperature	Melt Mass	Solidify Mass
May 10-11 2013	Nothing	.958 kWh	.753 kWh	21.399%	26 C (78.8 F)	N/A	N/A
May 11-12 2013	Blind System	.554 kWh	.048 kWh	91.366%	32 C (89.6 F)	100%	75%
Percentage Decrease in Energy Consumption with Blind System (Subtract Energy Consumption Decrease of Blind System from Nothing)				69.967%			

The blind system kept the Experiment hutch above 75 F throughout the night, so it has potential to save even more energy than shown. We would like to have the ability to test the blind system during the Winter months and in a larger setting to test its actual maximum output versus theoretical.

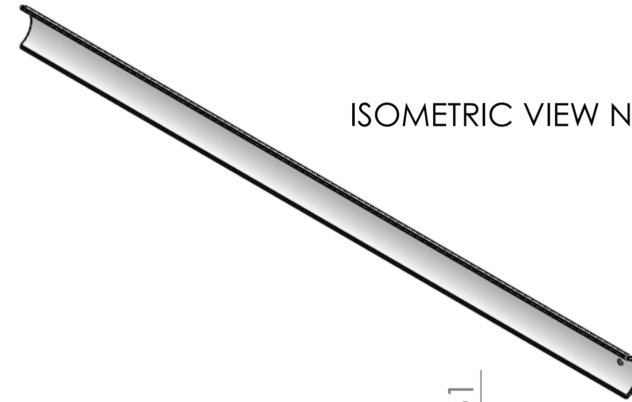
Theoretically, the blind system has potential to save **$1375.78** in utility costs over the course of 10 years, and our current results yields a minimum cost and energy savings of **$30.66** and **109.5 kWh** during the summer months in the 8' x 8' x 12' hutches.



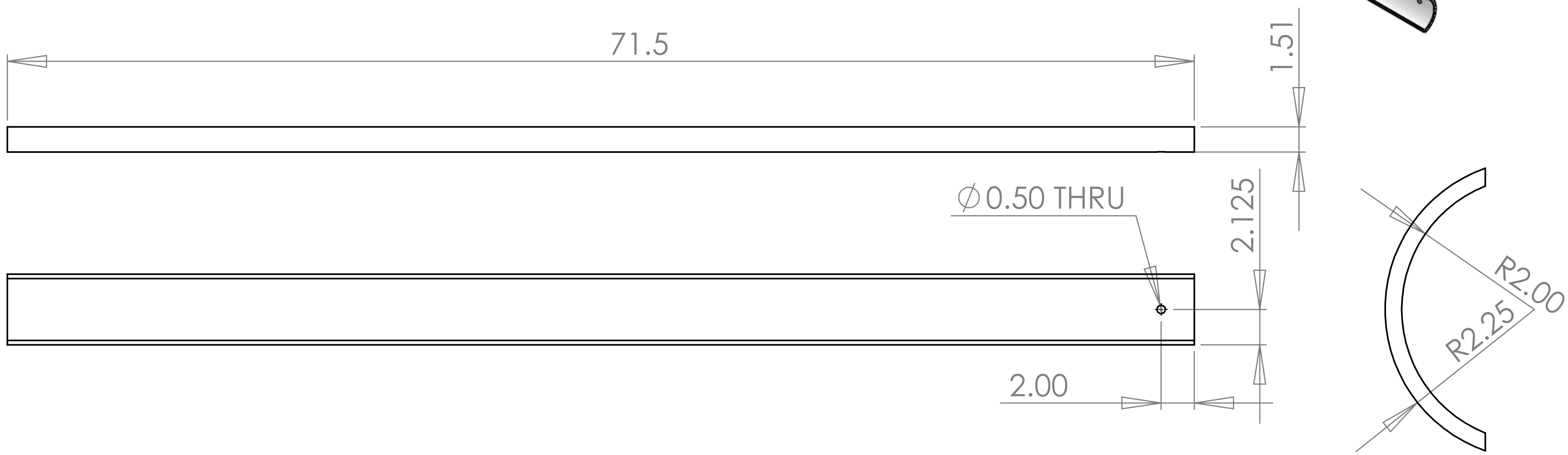


Chapter A.14: Component Drawings

TAB	DESCRIPTION	REV
00011-01	ELLIPTIC BACK	02



ISOMETRIC VIEW NOT TO SCALE



SIDE VIEW
NOT TO SHEET SCALE
1:2.5

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	APPROVALS	NAME	DATE
INCH STANDARD TOLERANCES: .X ± .1; .XX ± .01; .XXX ± .005; .XXXX ± .0005	DRAWN	ALI NASH	18 MAR 2013
	CHECKED	ALI NASH	18 MAR 2013
	ENGINEER	ALEX ZATOPA	18 MAR 2013
	DESIGNER	ALEX ZATOPA	18 MAR 2013
ANGLES ± 1 DEGREE	UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.		
MATERIAL ABS			
FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT) N/A			
DO NOT SCALE DRAWING			

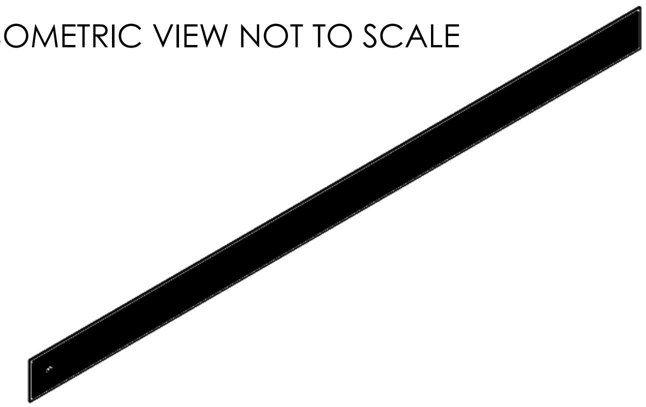
M^3

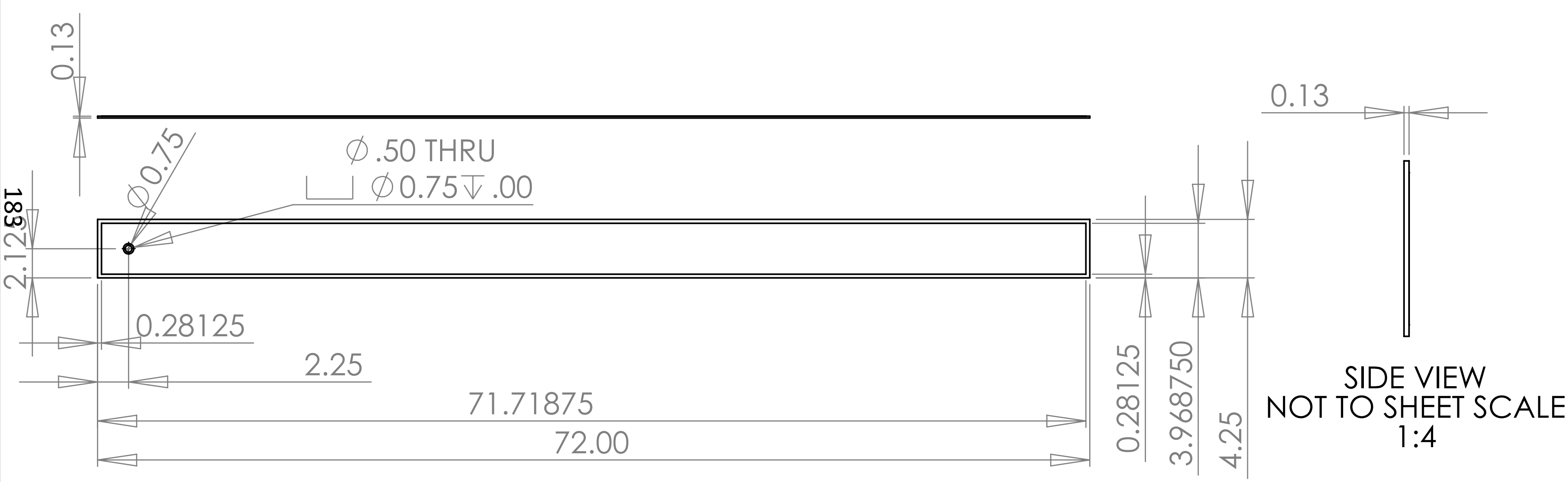
TITLE: ELLIPTIC BACK

SIZE	DWG. NO.	REV
A	00011	02
SCALE: 1:10		SHEET 1 OF 1

TAB	DESCRIPTION	REV
00012-01	LOUVER FACE	02

ISOMETRIC VIEW NOT TO SCALE





SIDE VIEW
NOT TO SHEET SCALE
1:4

NOTES: (UNLESS OTHERWISE SPECIFIED)

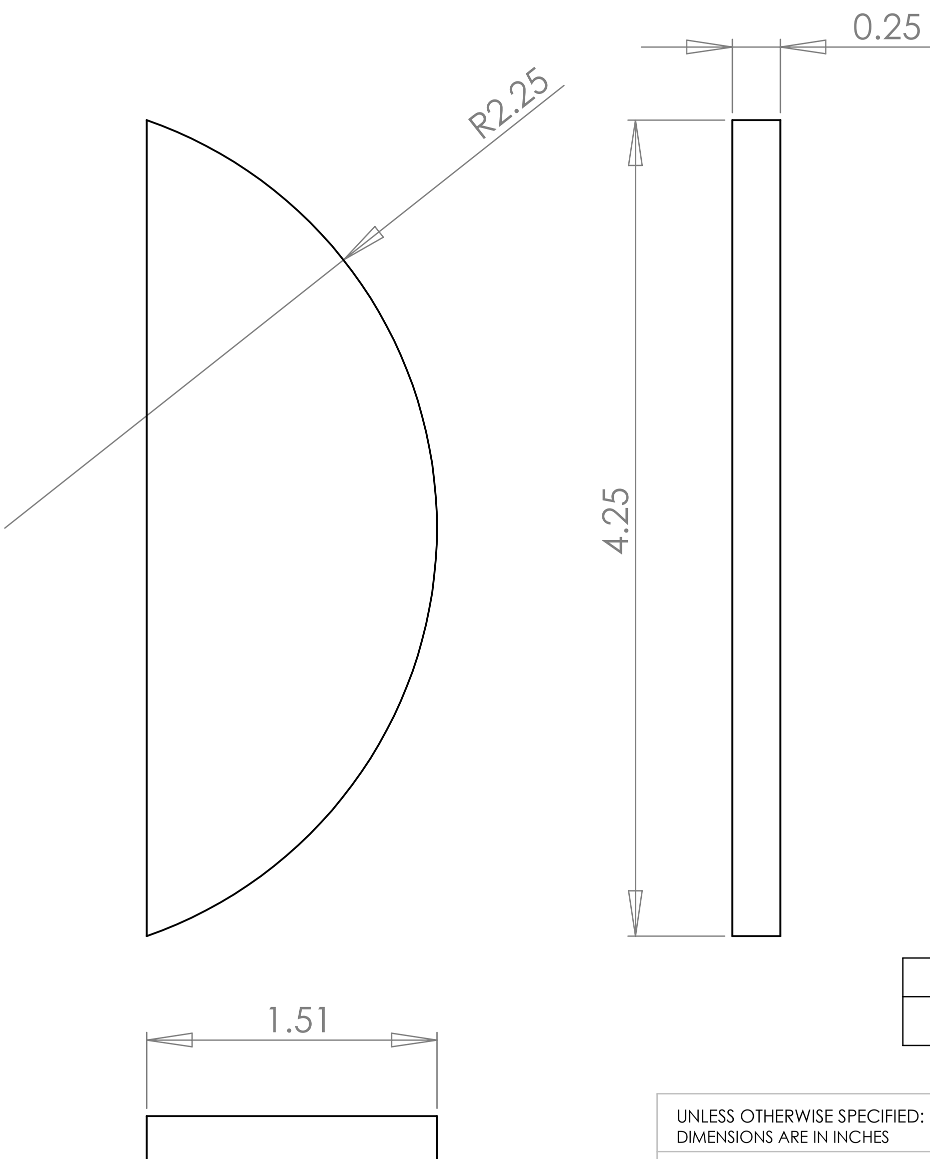
1. INNER RECTANGLE DIMENSIONSARE FOR BLACK PAINT FINISH ON ONE SIDE OF ACRYLIC

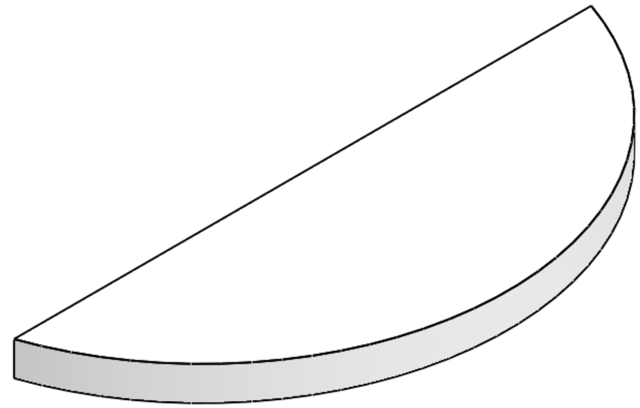
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	APPROVALS	NAME	DATE
INCH STANDARD TOLERANCES: .X ± .1 .XX ± .01 .XXX ± .005 .XXXX ± .0005	DRAWN	ALI NASH	18 MAR 2013
	CHECKED	ALI NASH	18 MAR 2013
	ENGINEER	ALEX ZATOPA	18 MAR 2013
	DESIGNER	ALEX ZATOPA	18 MAR 2013
ANGLES ± 1 DEGREE	UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.		
MATERIAL ACRYLIC			
FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT) BLACK PAINT			
DO NOT SCALE DRAWING			

M^3

TITLE: LOUVER FACE

SIZE	DWG. NO.	REV
A	00012	02
SCALE: 1:12		SHEET 1 OF 1





ISOMETRIC VIEW NOT TO SCALE

TAB	DESCRIPTION	REV
00035-01	SUPPORT SHEET BOTTOM	02

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

MATERIAL
ABS

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

DO NOT SCALE DRAWING

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

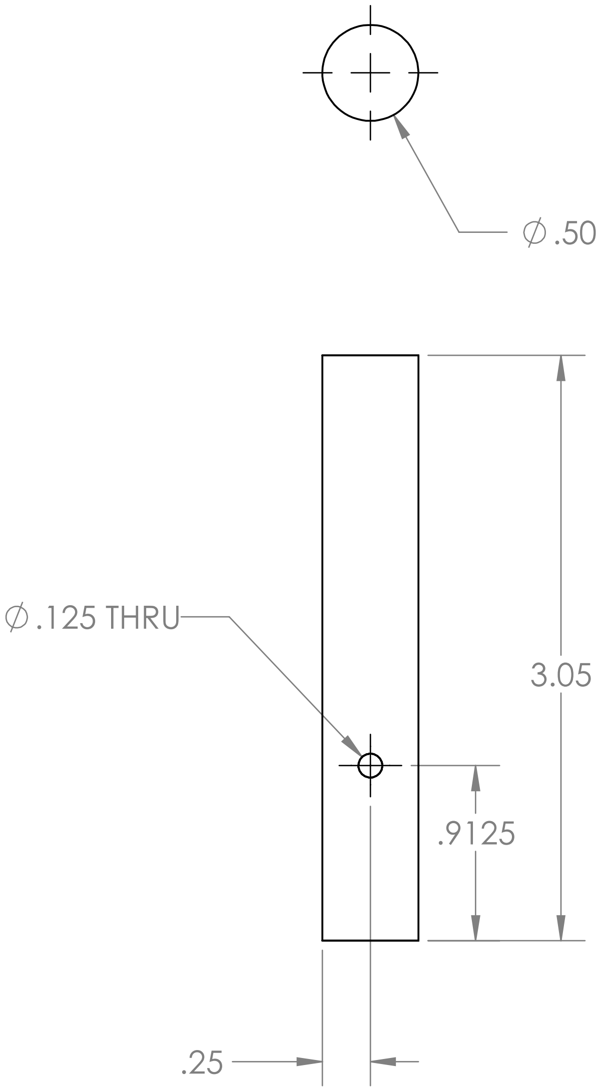
M^3

TITLE:
END CAP

SIZE A | DWG. NO. 00013 | REV 02

SCALE: 1:1 | SHEET 1 OF 1

TAB	DESCRIPTION	REV
00028-01	DRIVE ROD	02



ISOMETRIC VIEW NOT TO SCALE

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	APPROVALS	NAME	DATE
INCH STANDARD TOLERANCES: .X ± .1; .XX ± .01; .XXX ± .005; .XXXX ± .0005	DRAWN	ALI NASH	18 MAR 2013
	CHECKED	ALI NASH	18 MAR 2013
	ENGINEER	ALEX ZATOPA	18 MAR 2013
	DESIGNER	ALEX ZATOPA	18 MAR 2013
ANGLES ± 1 DEGREE	UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.		
MATERIAL AISI 304			
FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT) N/A			
DO NOT SCALE DRAWING			

M 3

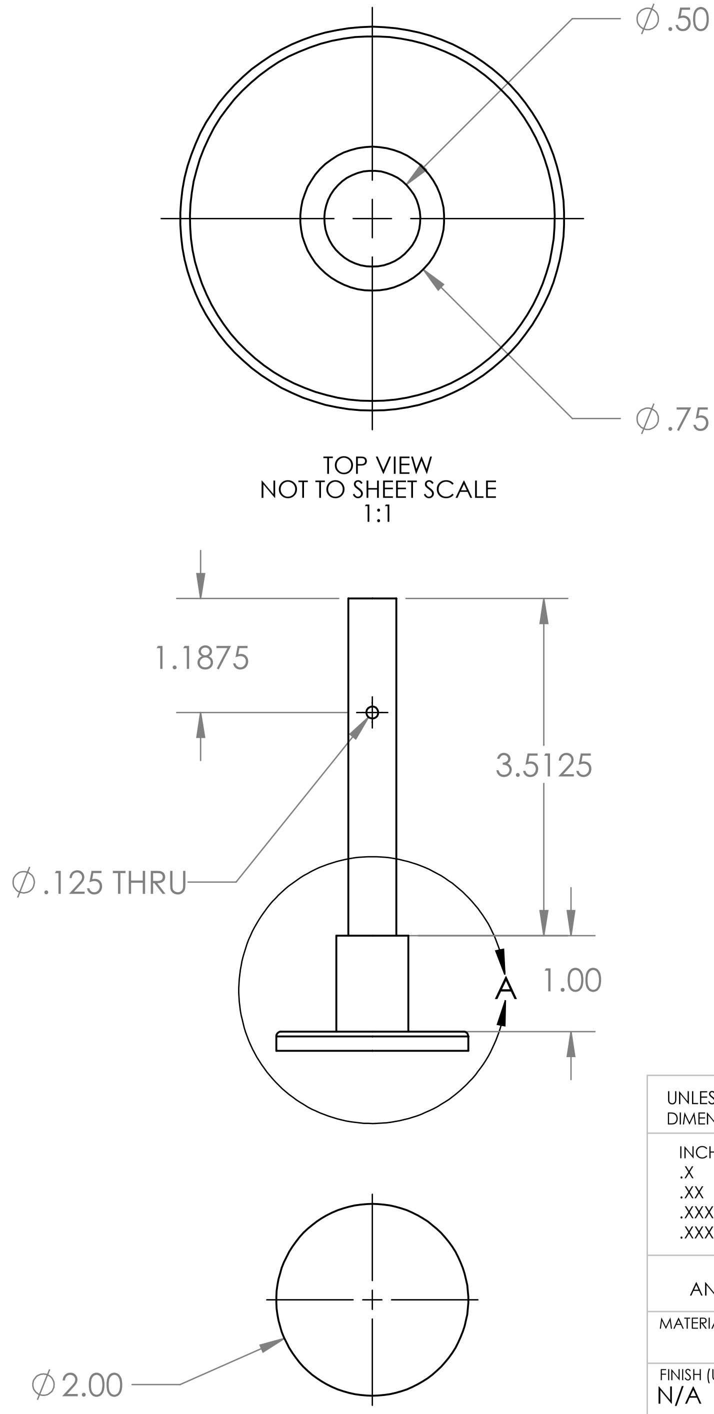
PROPRIETARY AND CONFIDENTIAL

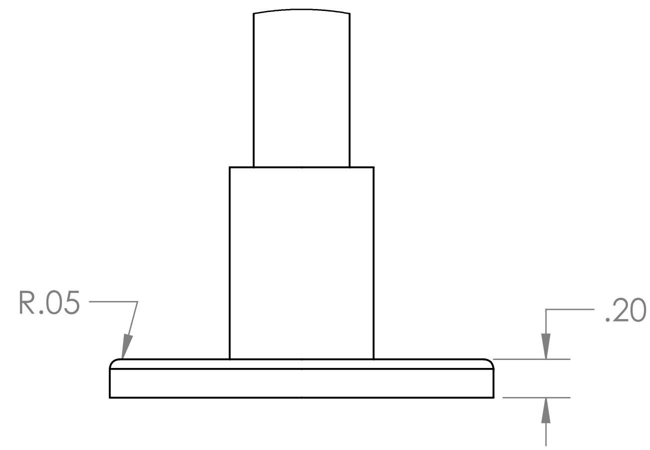
TITLE: DRIVE ROD

SIZE	DWG. NO.	REV
A	00028	02

SCALE: 1:1 | SHEET 1 OF 1

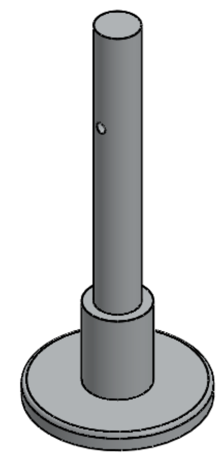
TAB	DESCRIPTION	REV
00029-01	POST BOTTOM	02





DETAIL A
SCALE 1 : 1

ISOMETRIC VIEW NOT TO SCALE



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	APPROVALS	NAME	DATE
INCH STANDARD TOLERANCES: .X ± .1, .XX ± .01, .XXX ± .005, .XXXX ± .0005	DRAWN	ALI NASH	18 MAR 2013
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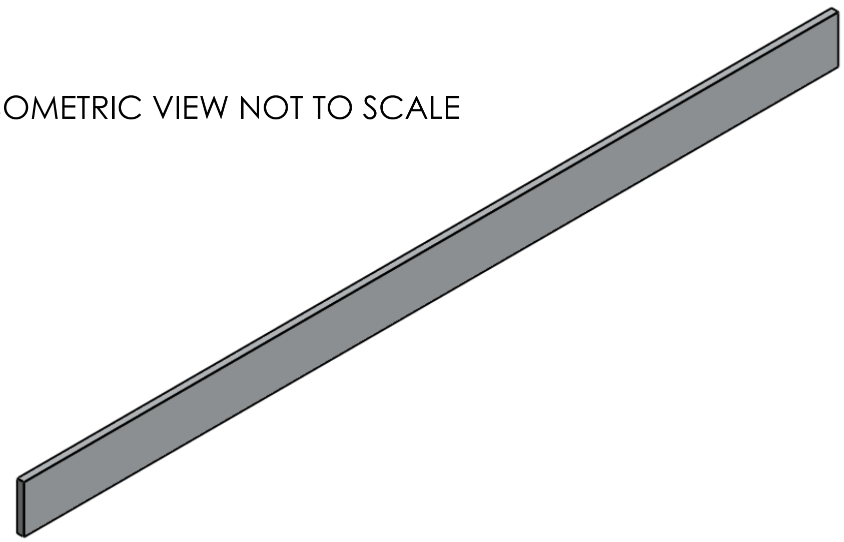
	ENGINEER	ALEX ZATOPA	18 MAR 2013
	DESIGNER	ALEX ZATOPA	18 MAR 2013
ANGLES ± 1 DEGREE	UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.		
MATERIAL 6061 ALLOY			
FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT) N/A			
DO NOT SCALE DRAWING			

M^3

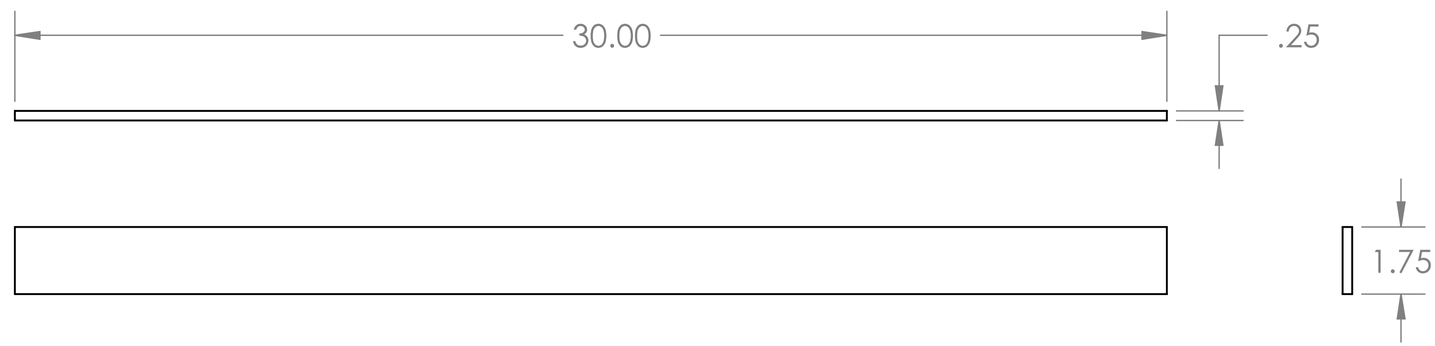
TITLE: POST BOTTOM

SIZE	DWG. NO.	REV
A	00029	02
SCALE: 1:2		SHEET 1 OF 1

ISOMETRIC VIEW NOT TO SCALE



TAB	DESCRIPTION	REV
00030-01	RACK SUPPORT	02



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

MATERIAL
6061 ALLOY

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

DO NOT SCALE DRAWING

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

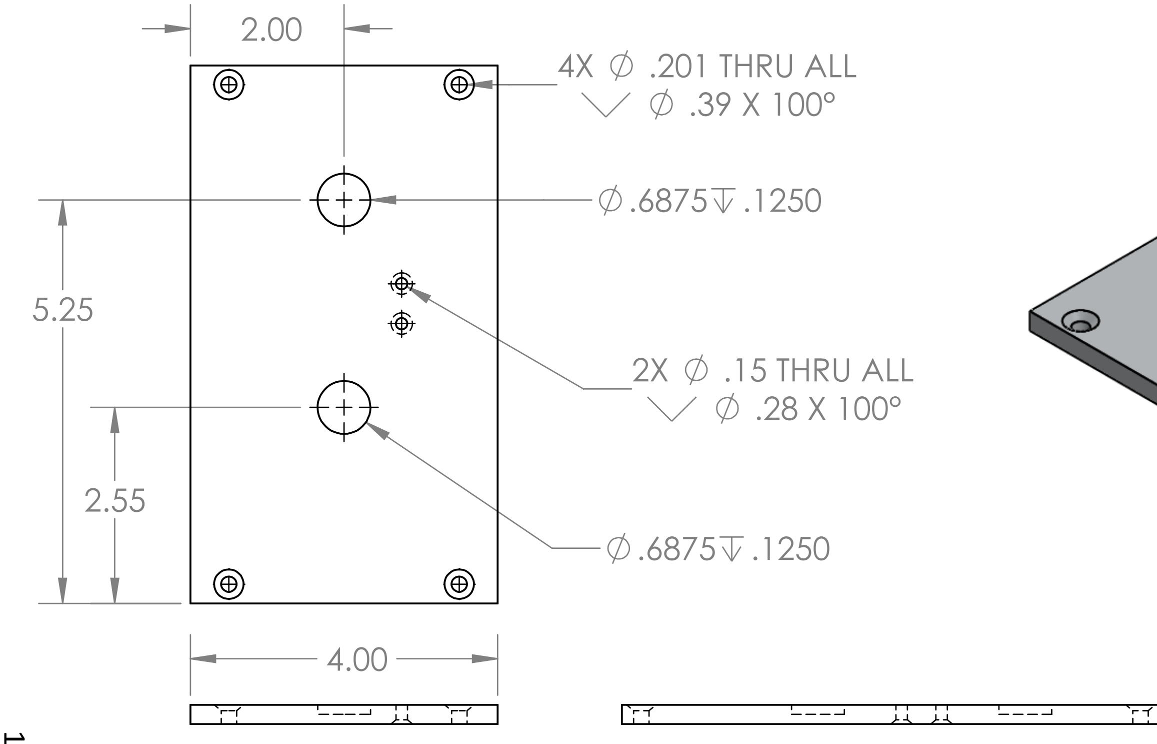
M 3

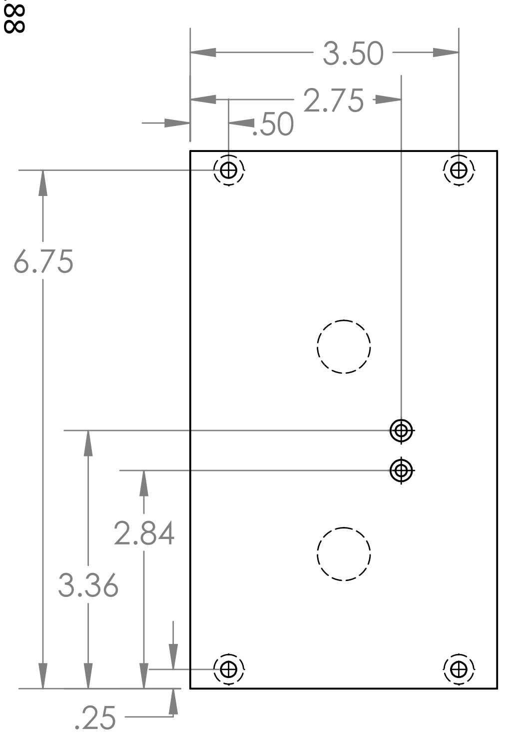
TITLE:
RACK SUPPORT

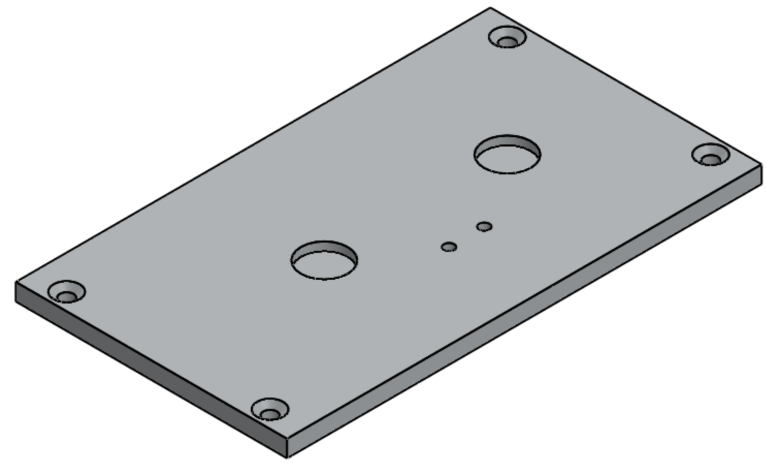
SIZE	DWG. NO.	REV
A	00030	02

SCALE: 1:5

SHEET 1 OF 1







ISOMETRIC VIEW NOT TO SCALE

TAB	DESCRIPTION	REV
00035-01	SUPPORT SHEET BOTTOM	02

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

MATERIAL
6061 ALLOY

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

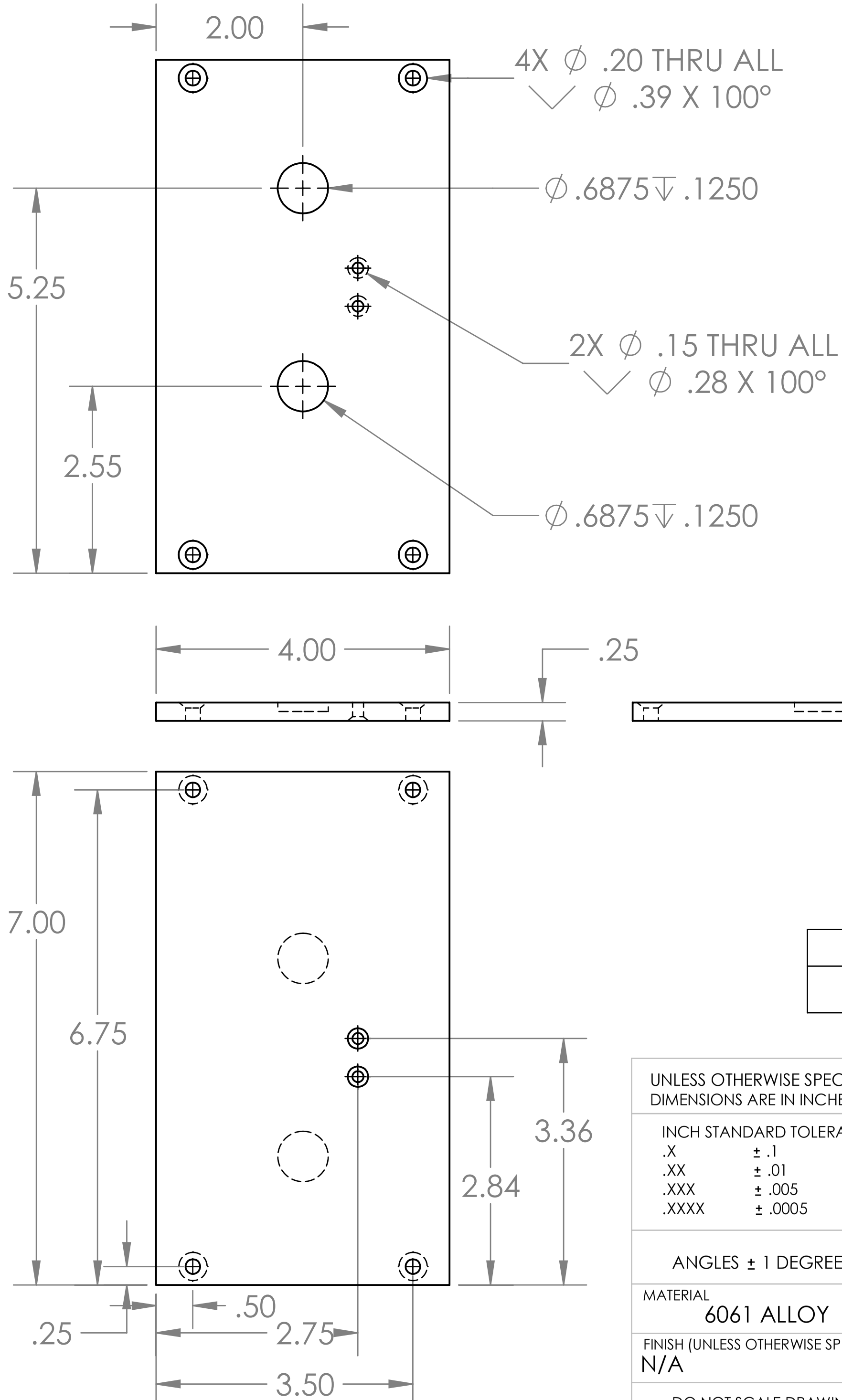
DO NOT SCALE DRAWING

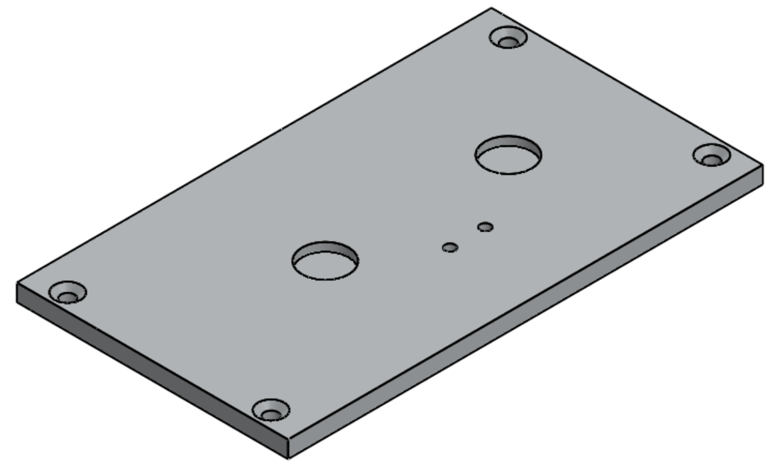
M[3]

TITLE:
SUPPORT SHEET BOTTOM

SIZE	DWG. NO.	REV
A	00035	02

SCALE: 1:2.5 | SHEET 1 OF 1





ISOMETRIC VIEW NOT TO SCALE

TAB	DESCRIPTION	REV
00036-01	SUPPORT SHEET EDGE BOTTOM	02

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

MATERIAL
6061 ALLOY

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

DO NOT SCALE DRAWING

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

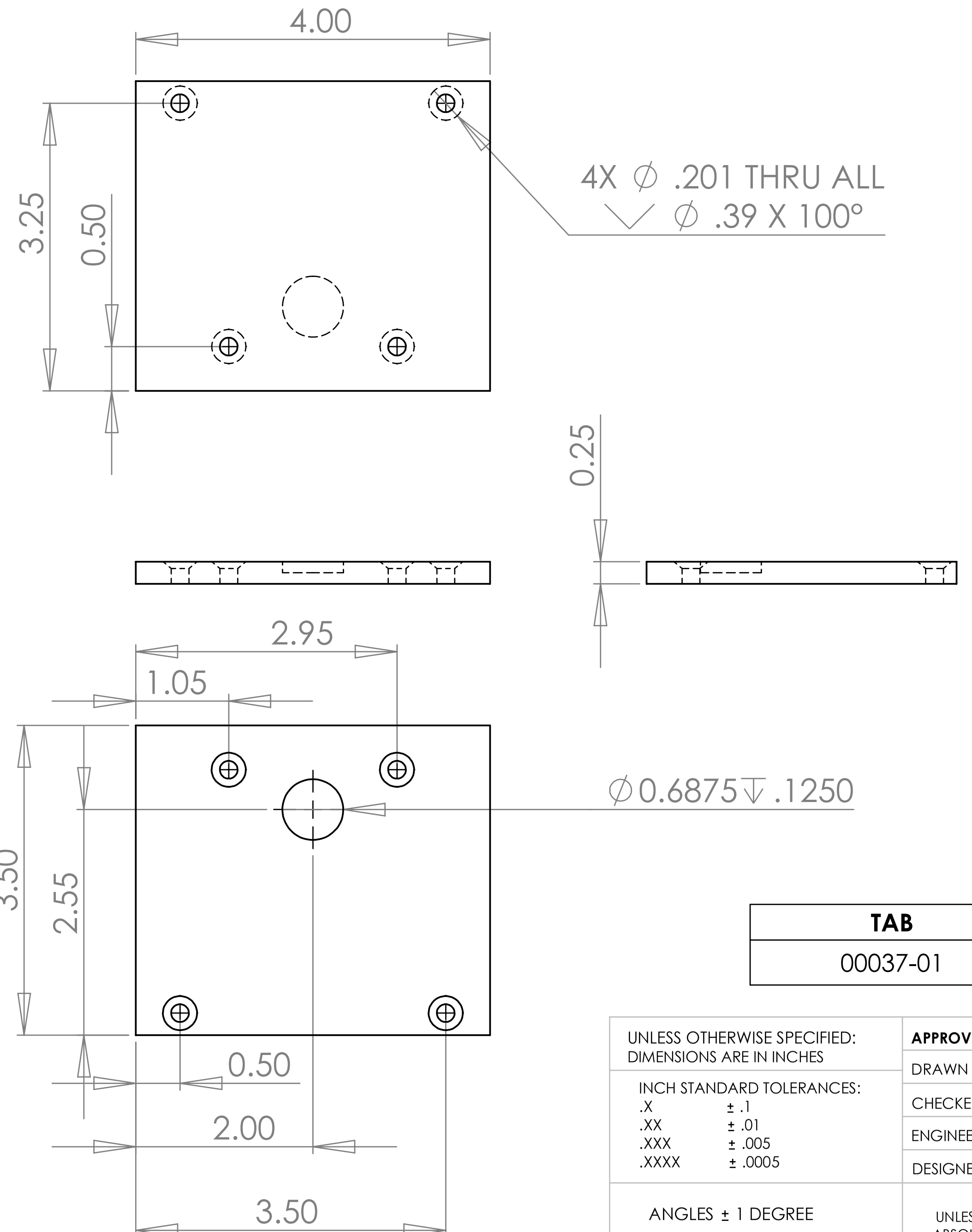
UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

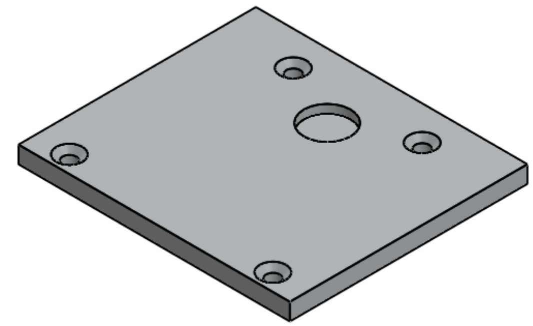
M^3

TITLE:
SUPPORT SHEET EDGE BOTTOM

SIZE A | DWG. NO. 00036 | REV 02

SCALE: 1:2.5 | SHEET 1 OF 1





ISOMETRIC VIEW NOT TO SCALE

TAB	DESCRIPTION	REV
00037-01	SUPPORT SHEET MIDDLE BOTTOM	02

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

MATERIAL
6061 ALLOY

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

DO NOT SCALE DRAWING

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

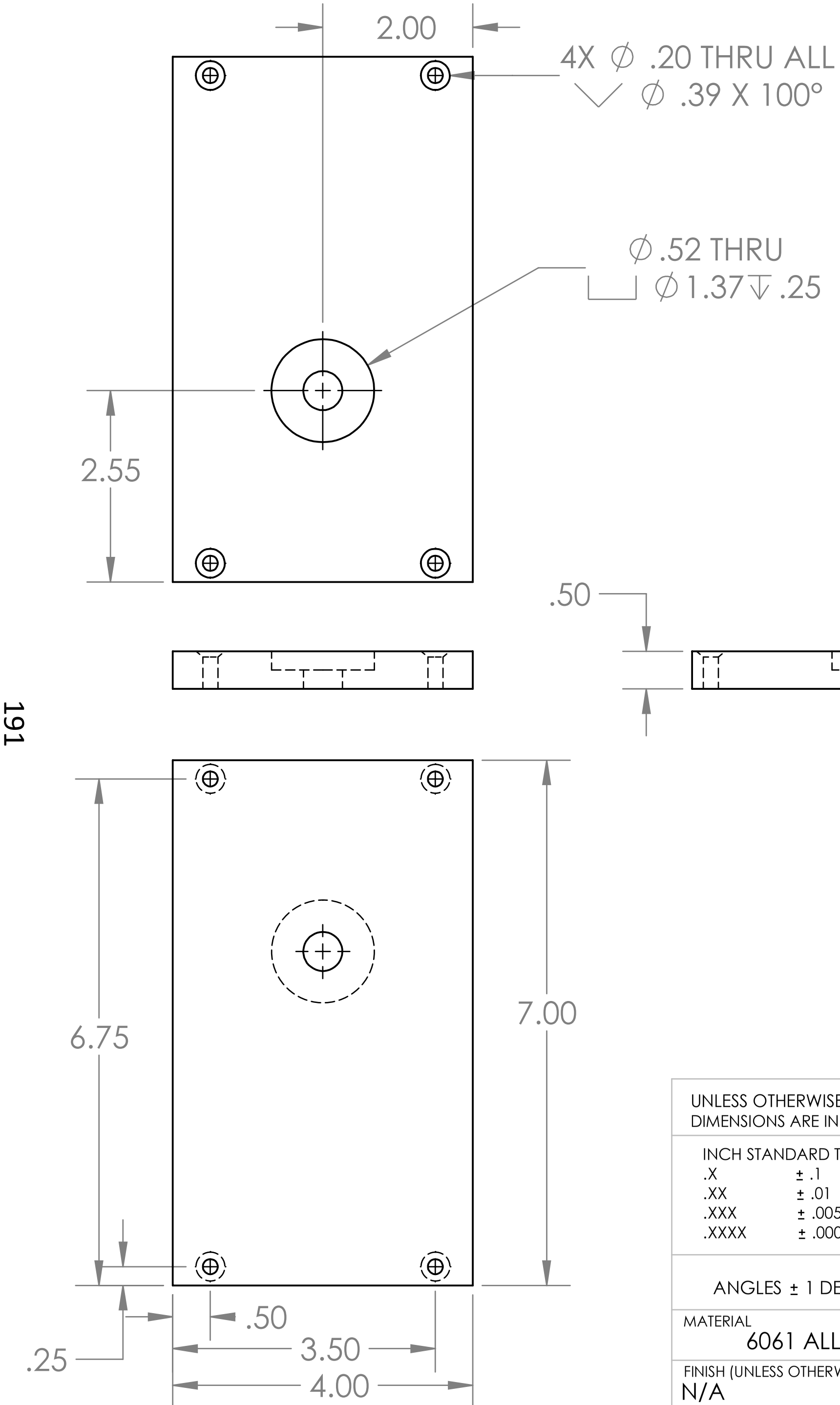
UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

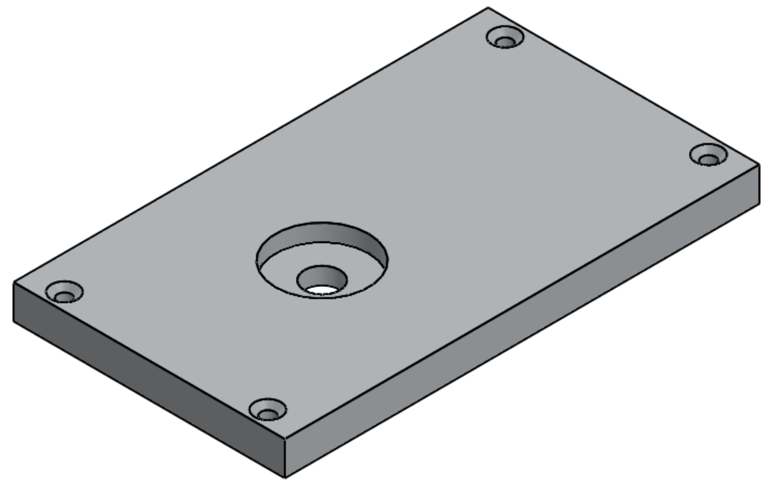
M^3

TITLE:
SUPPORT SHEET MIDDLE BOTTOM

SIZE A | DWG. NO. 00037 | REV 02

SCALE: 1:2 | SHEET 1 OF 1





ISOMETRIC VIEW NOT TO SCALE

TAB	DESCRIPTION	REV
00039-01	SUPPORT SHEET TOP	02

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

MATERIAL
6061 ALLOY

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

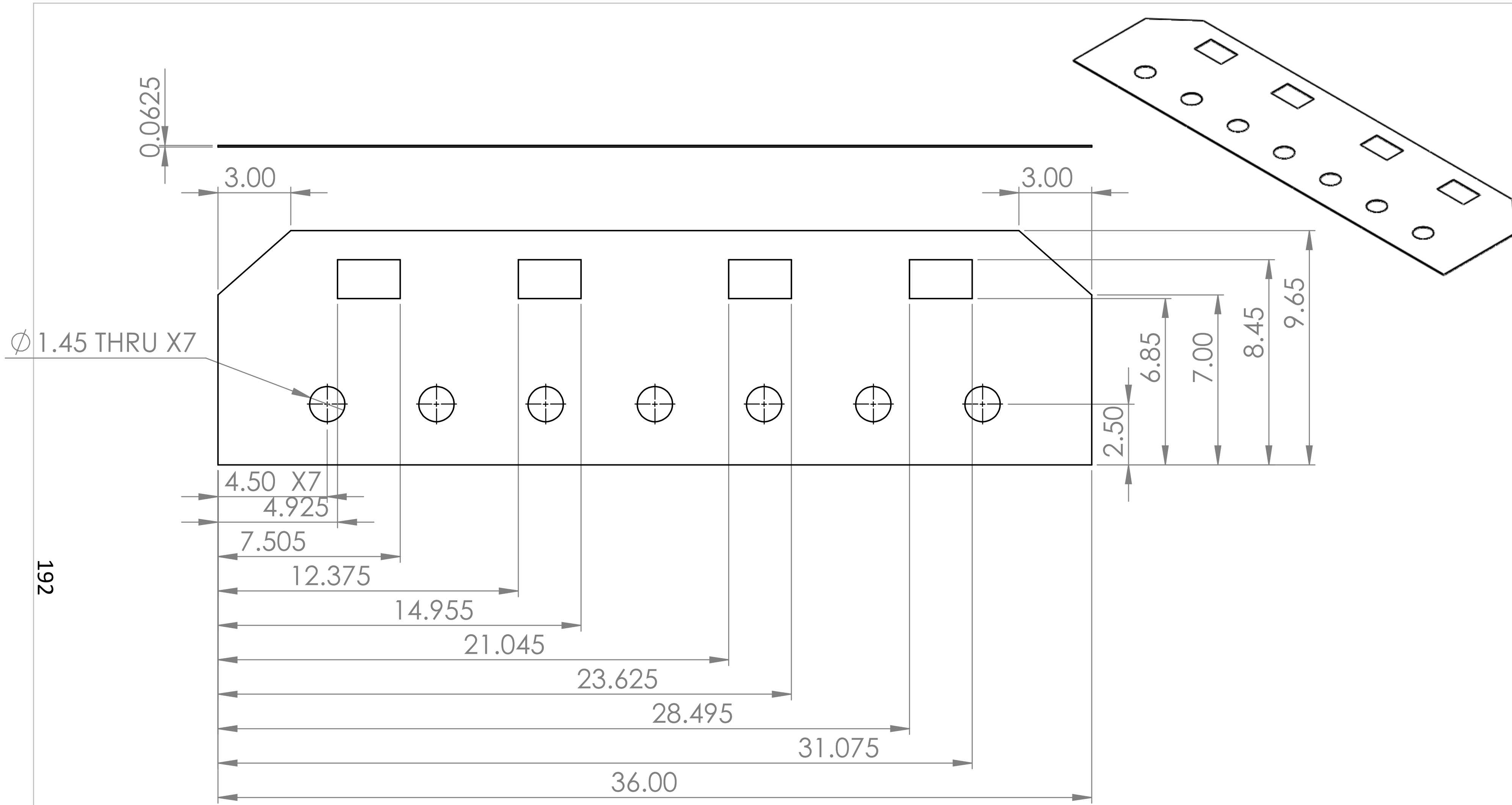
DO NOT SCALE DRAWING

M^3

TITLE:
SUPPORT SHEET TOP

SIZE A | DWG. NO. 00039 | REV 02

SCALE: 1:2.5 | SHEET 1 OF 1



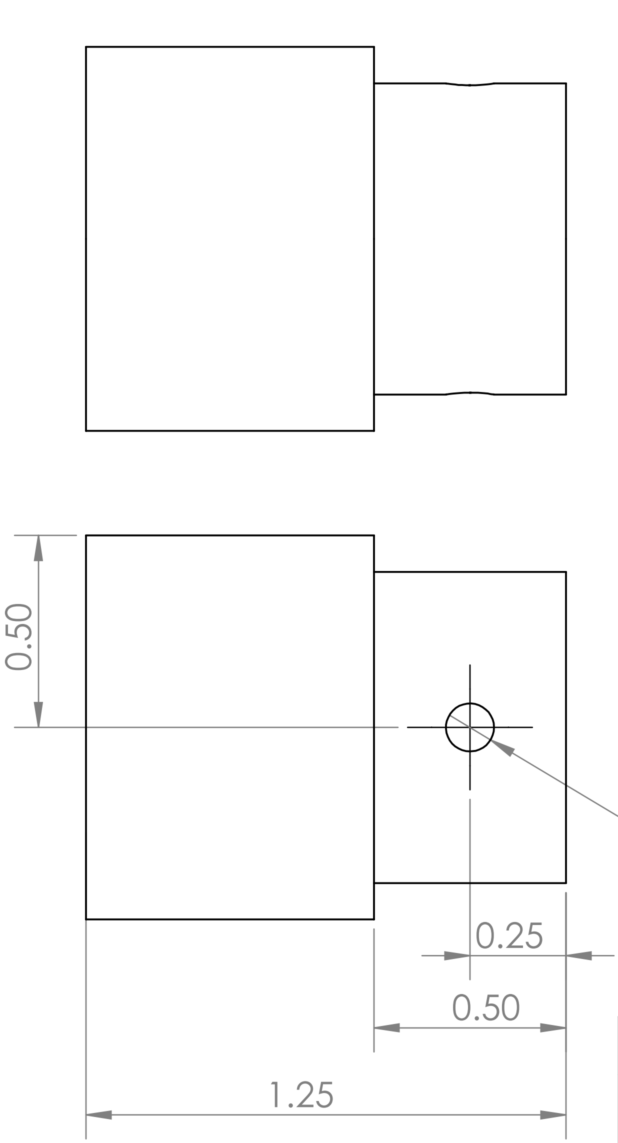
UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	APPROVALS	NAME	DATE
INCH STANDARD TOLERANCES: .X ± .1 .XX ± .01 .XXX ± .005 .XXXX ± .0005	DRAWN	ALI NASH	18 MAR 2013
	CHECKED	ALI NASH	18 MAR 2013
	ENGINEER	ALEX ZATOPA	18 MAR 2013
	DESIGNER	ALEX ZATOPA	18 MAR 2013
ANGLES ± 1 DEGREE	UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.		
MATERIAL PVC			
FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT) N/A			
DO NOT SCALE DRAWING			

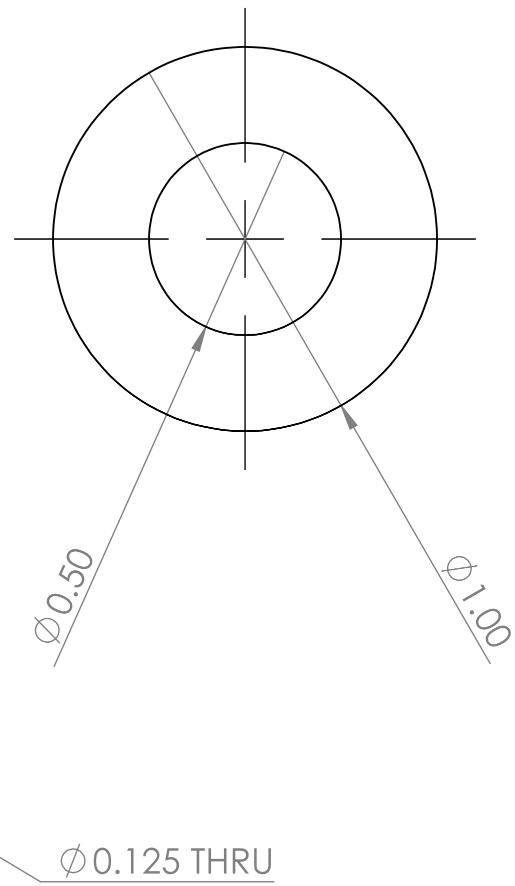
M^3

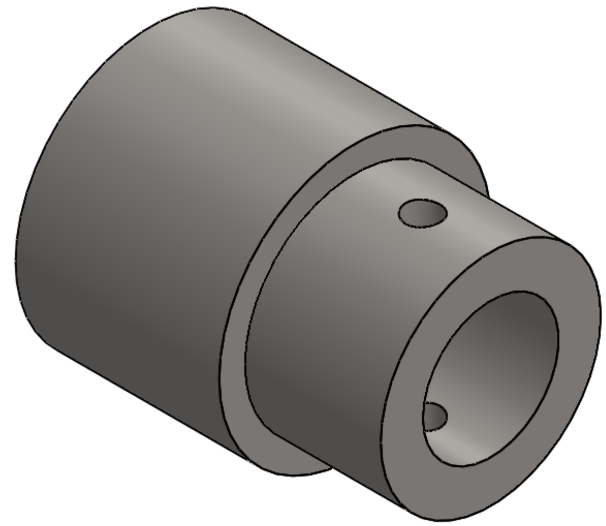
TITLE:

TOP SHEET

SIZE	DWG. NO.	REV
A	00040	02
SCALE: 1:10		SHEET 1 OF 1







UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

MATERIAL
STEEL PLAIN

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

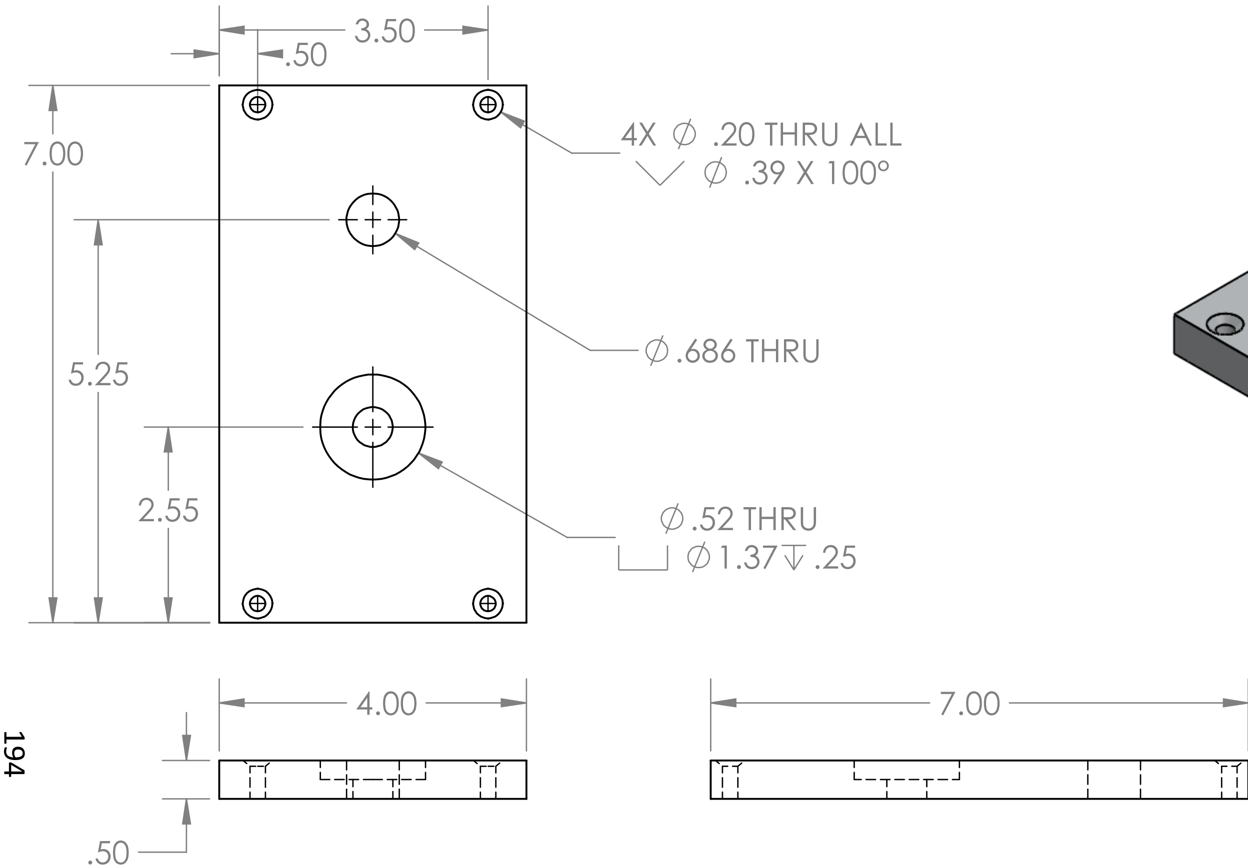
DO NOT SCALE DRAWING

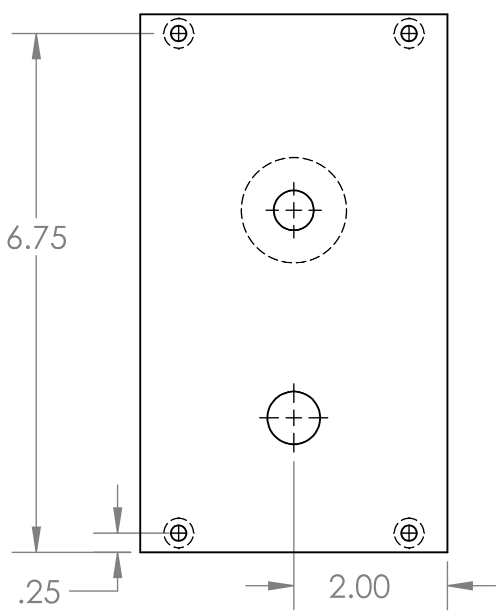
M[3]

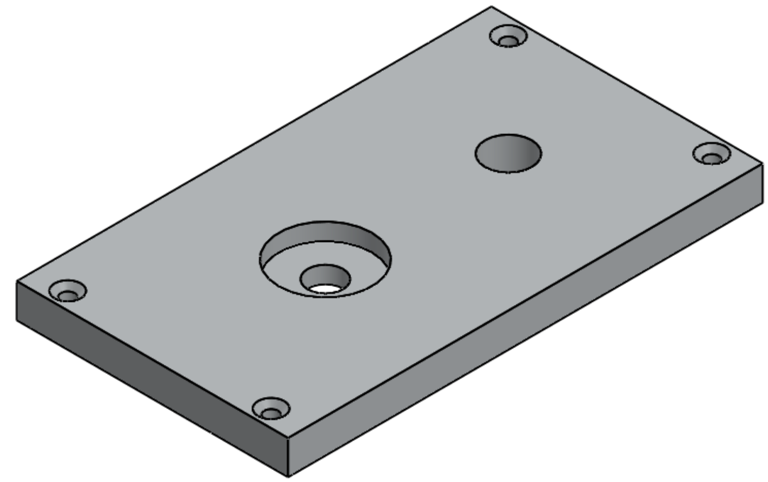
TITLE:
WORM GEAR

SIZE A | DWG. NO. 00042 | REV 02

SCALE: 2:1 | SHEET 1 OF 1







ISOMETRIC VIEW NOT TO SCALE

TAB	DESCRIPTION	REV
00044-01	SUPPORT SHEET TOP EDGE	01

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	APPROVALS	NAME	DATE
INCH STANDARD TOLERANCES: .X ± .1 .XX ± .01 .XXX ± .005 .XXXX ± .0005	DRAWN	ALI NASH	18 MAR 2013
	CHECKED	ALI NASH	18 MAR 2013
	ENGINEER	ALEX ZATOPA	18 MAR 2013
	DESIGNER	ALEX ZATOPA	18 MAR 2013
ANGLES ± 1 DEGREE	UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.		
MATERIAL 6061 ALLOY			
FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT) N/A			
DO NOT SCALE DRAWING			

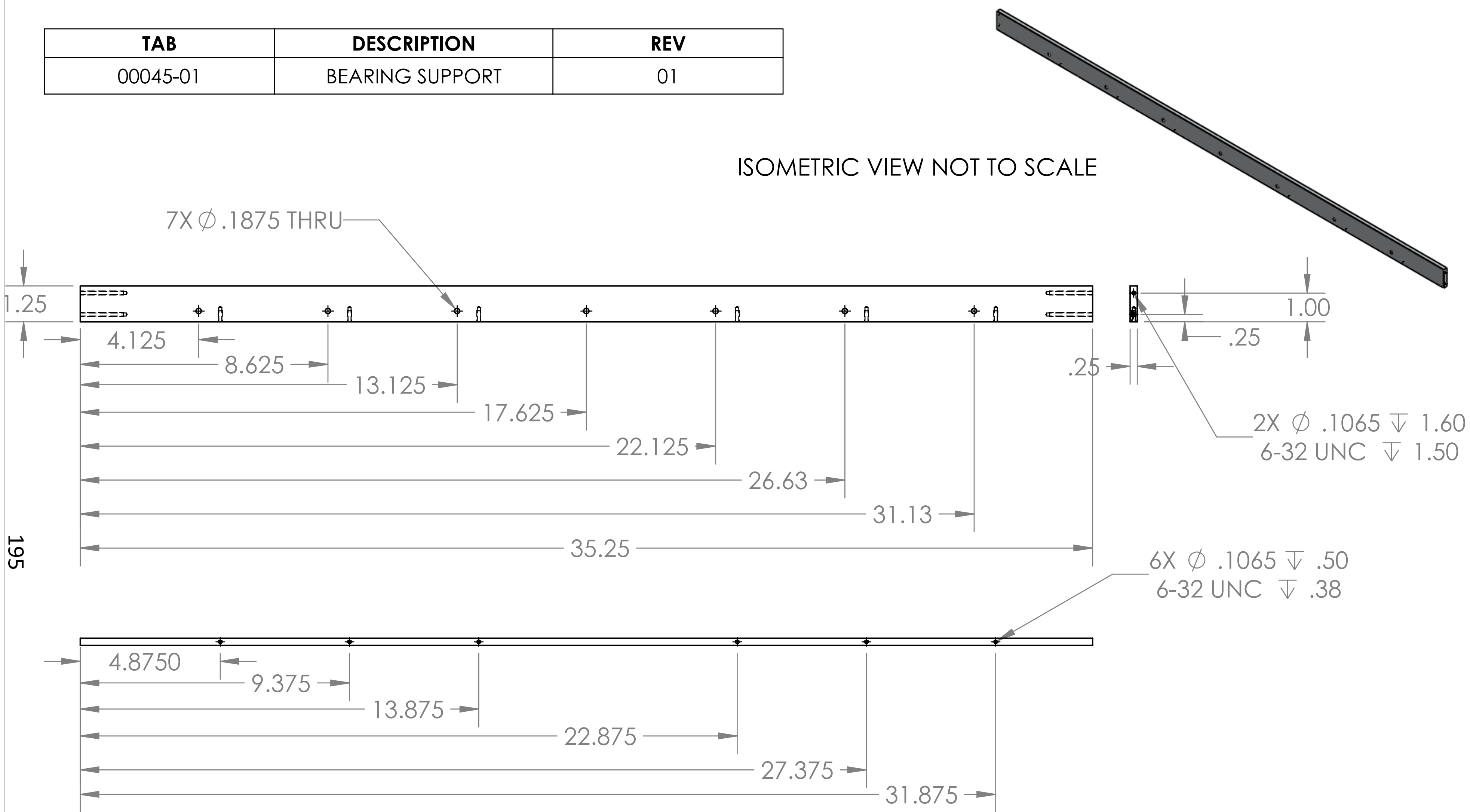
M³

TITLE: SUPPORT SHEET TOP EDGE

SIZE	DWG. NO.	REV
A	00044	01

SCALE: 1:2.5 | SHEET 1 OF 1

TAB	DESCRIPTION	REV
00045-01	BEARING SUPPORT	01

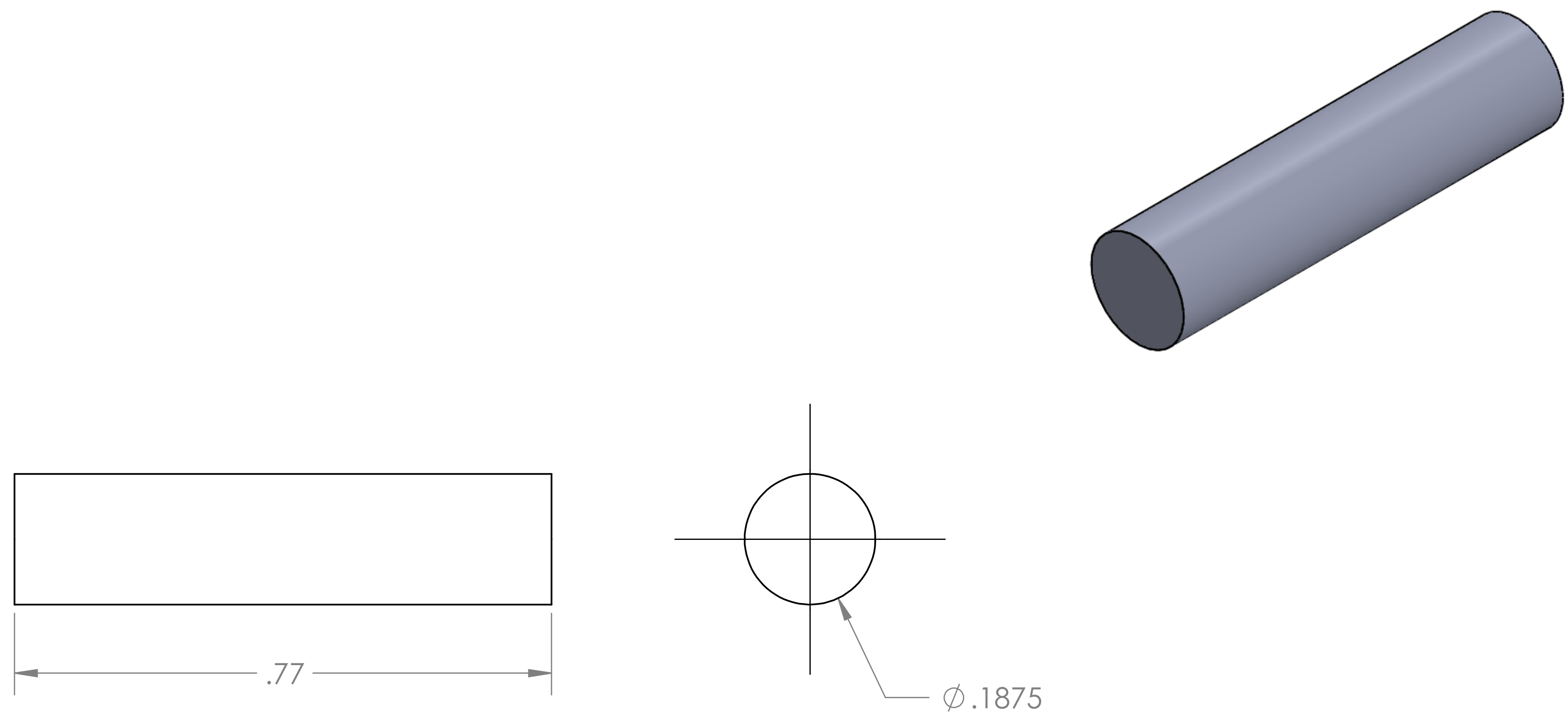


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	APPROVALS	NAME	DATE
INCH STANDARD TOLERANCES: .X ± .1, .XX ± .01, .XXX ± .005, .XXXX ± .0005	DRAWN	ALI NASH	18 MAR 2013
	CHECKED	ALI NASH	18 MAR 2013
	ENGINEER	ALEX ZATOPA	18 MAR 2013
	DESIGNER	ALEX ZATOPA	18 MAR 2013
ANGLES ± 1 DEGREE	UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.		
MATERIAL 6061 ALLOY			
FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT) N/A			
DO NOT SCALE DRAWING			

M^3

TITLE: BEARING SUPPORT

SIZE	DWG. NO.	REV
A	00045	01
SCALE: 1:8	SHEET 1 OF 1	



TAB	DESCRIPTION	REV
00046-01	BEARING SUPPORT ROD	01

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

MATERIAL
AISI 304

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

DO NOT SCALE DRAWING

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

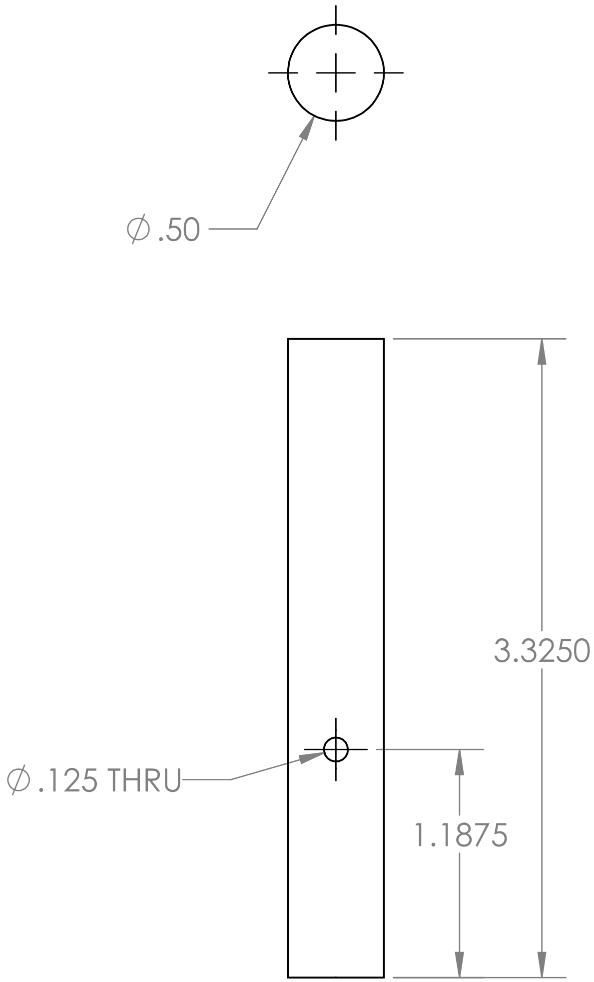
UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

M 3

TITLE:
BEARING SUPPORT ROD

SIZE A | DWG. NO. 00046 | REV 01

SCALE: 4:1 | SHEET 1 OF 1



ISOMETRIC VIEW NOT TO SCALE

TAB	DESCRIPTION	REV
00047-01	END POST	01

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

MATERIAL
6061 ALLOY

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

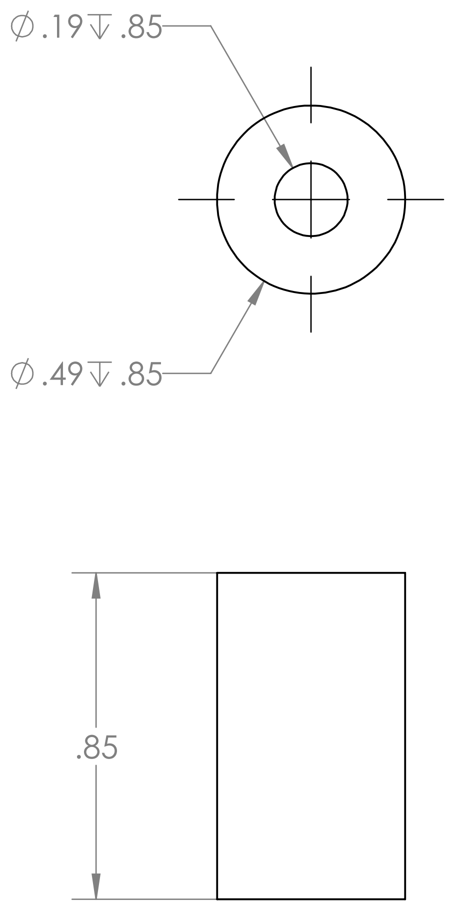
DO NOT SCALE DRAWING

M 3

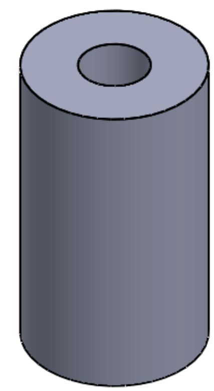
TITLE:
END POST

SIZE A | DWG. NO. 00047 | REV 01

SCALE: 1:1 | SHEET 1 OF 1



ISOMETRIC VIEW NOT TO SCALE



TAB	DESCRIPTION	REV
00050-01	SPACER	01

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

MATERIAL
Delrin 2700 NC010

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

DO NOT SCALE DRAWING

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

M [3]

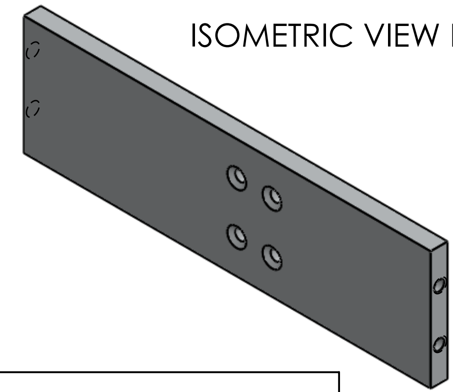
TITLE:
SPACER

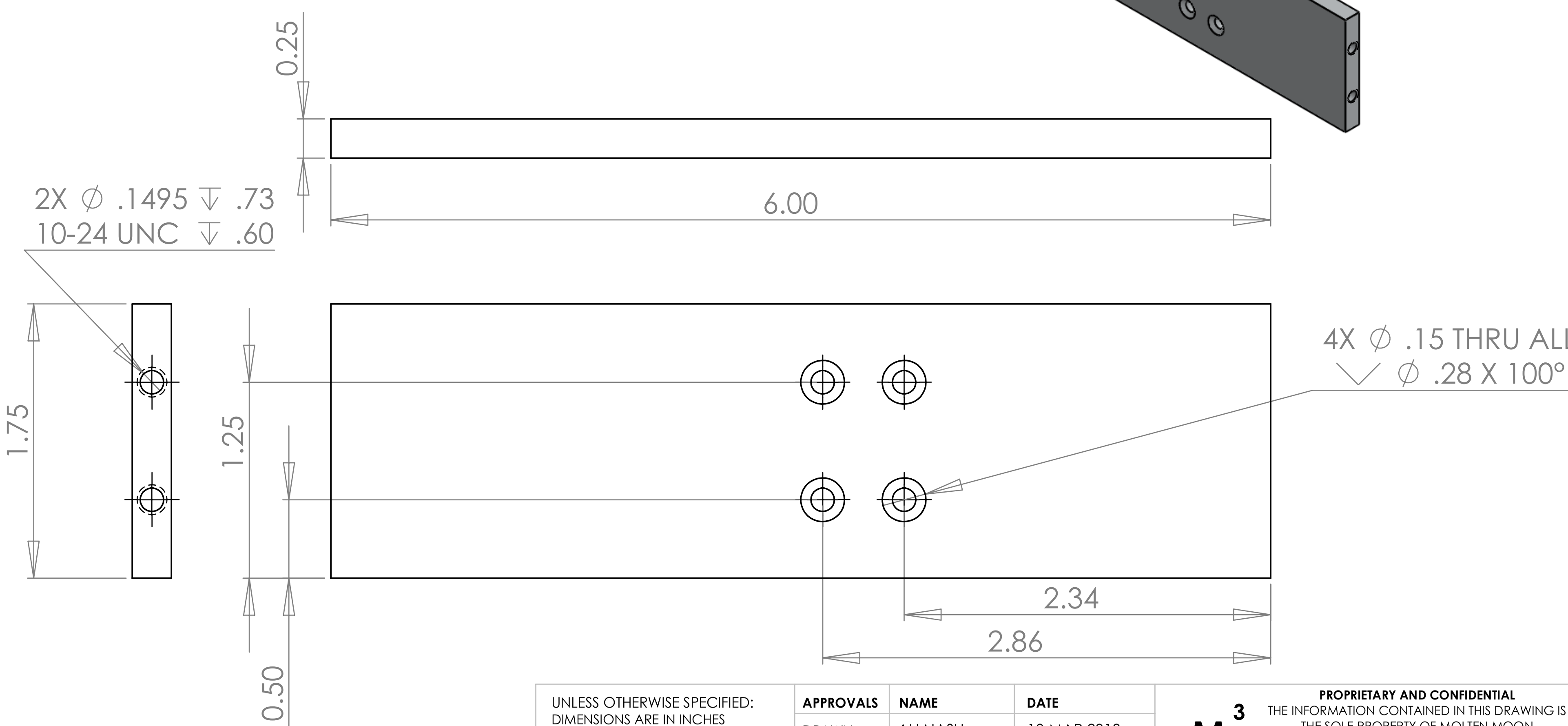
SIZE A | DWG. NO. 00050 | REV 01

SCALE: 2:1 | SHEET 1 OF 1

TAB	DESCRIPTION	REV
00051-01	END SUPPORT	01

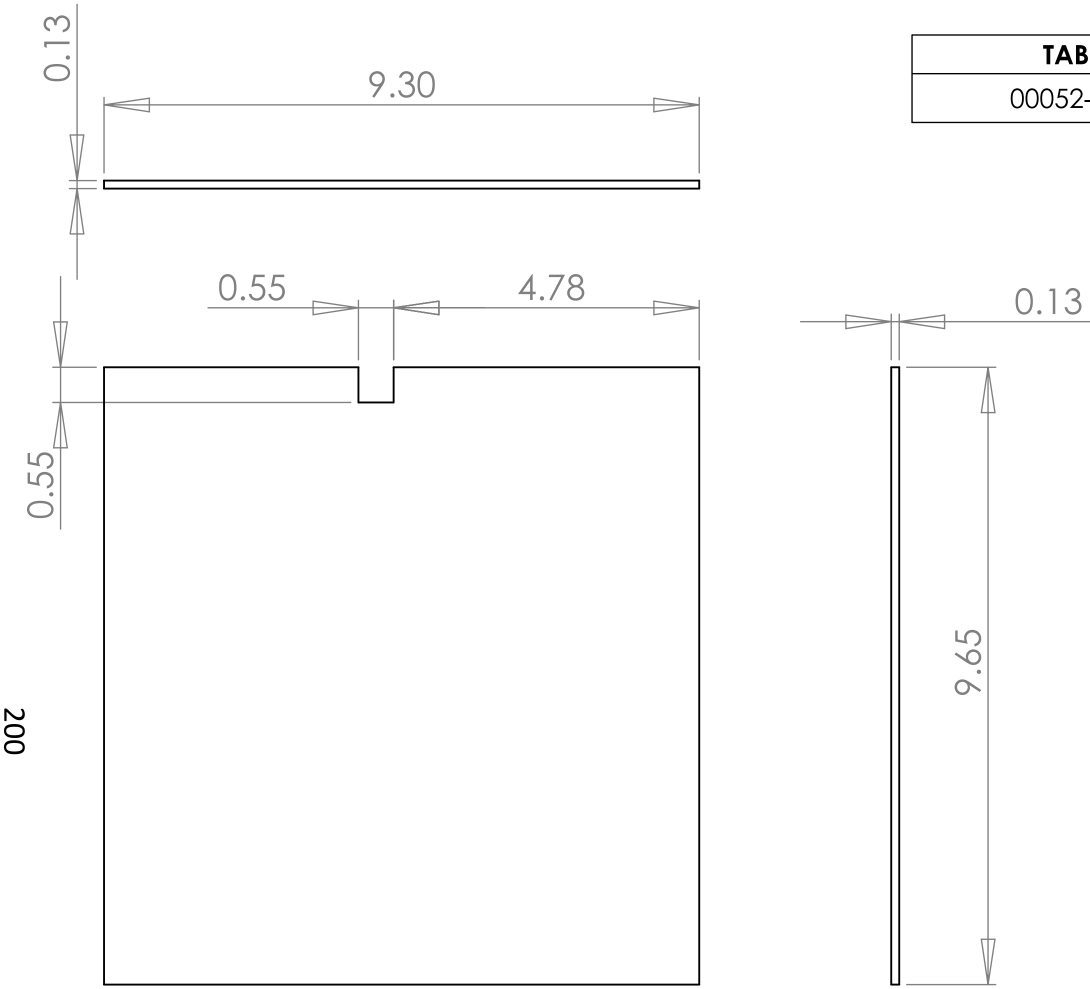
ISOMETRIC VIEW NOT TO SCALE



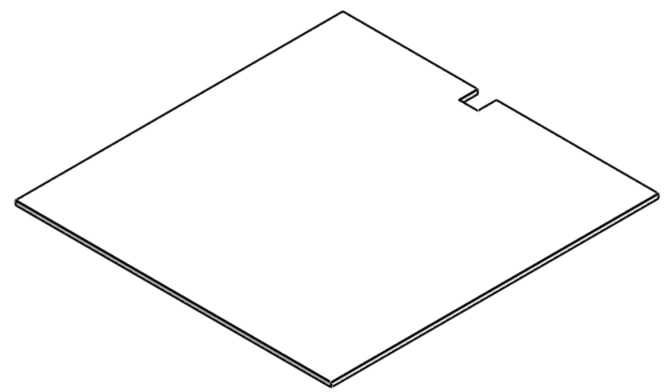


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	APPROVALS	NAME	DATE	**PROPRIETARY AND CONFIDENTIAL** THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF MOLTEN MOON MECHANICAL. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF MOLTEN MOON MECHANICAL IS PROHIBITED.
INCH STANDARD TOLERANCES: .X ± .1 .XX ± .01 .XXX ± .005 .XXXX ± .0005	DRAWN	ALI NASH	18 MAR 2013	**M**^{3}
	CHECKED	ALI NASH	18 MAR 2013	
	ENGINEER	ALEX ZATOPA	18 MAR 2013	TITLE: END SUPPORT
	DESIGNER	ALEX ZATOPA	18 MAR 2013	
ANGLES ± 1 DEGREE	UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.			SIZE **A**
MATERIAL 6061 ALLOY				DWG. NO. 00051
FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT) N/A				REV 01
DO NOT SCALE DRAWING				SCALE: 1:1
				SHEET 1 OF 1

TAB	DESCRIPTION	REV
00052-01	PVC PLATE	01



ISOMETRIC VIEW NOT TO SCALE



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

MATERIAL
PVC

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

DO NOT SCALE DRAWING

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

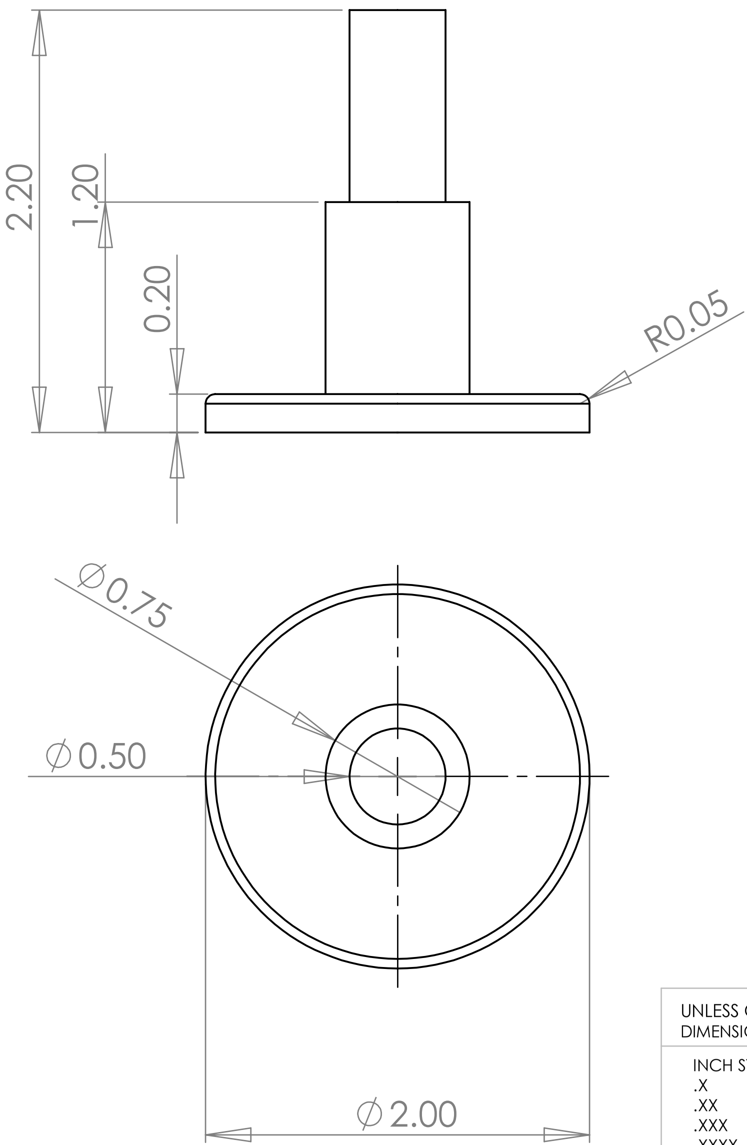
UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

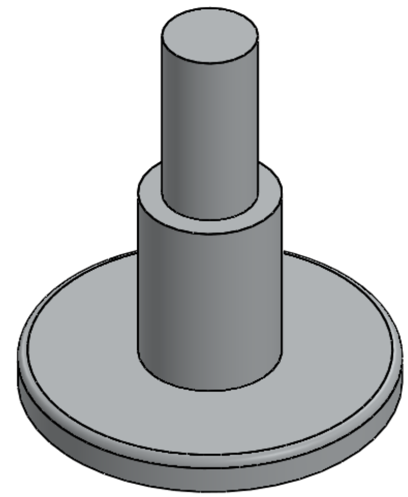
M 3

TITLE:
PVC PLATE

SIZE A | DWG. NO. 00052 | REV 01

SCALE: 1:3 | SHEET 1 OF 1





ISOMETRIC VIEW NOT TO SCALE

TAB	DESCRIPTION	REV
00053-01	POST TOP	01

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

MATERIAL
6061 ALLOY

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

DO NOT SCALE DRAWING

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

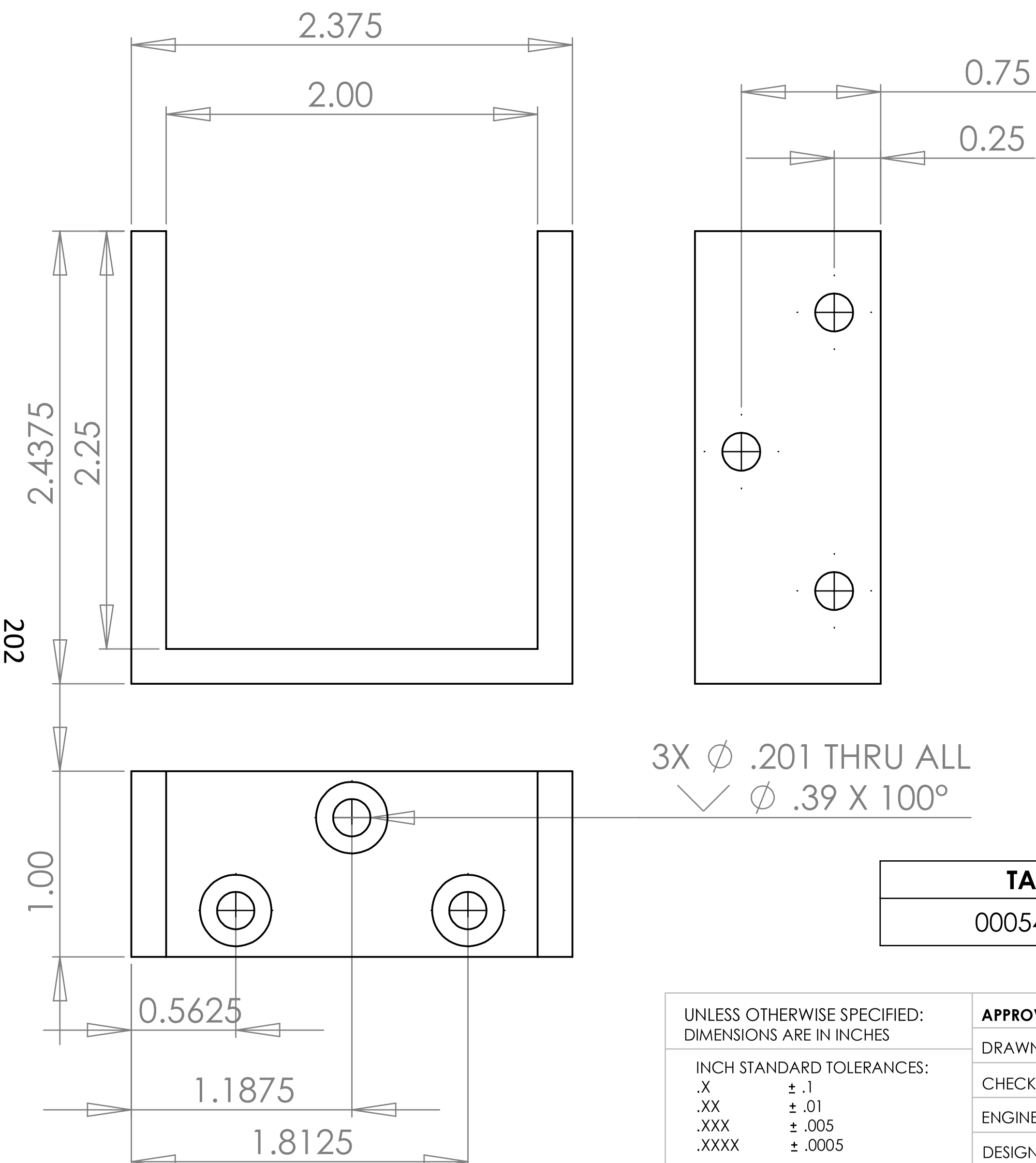
UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

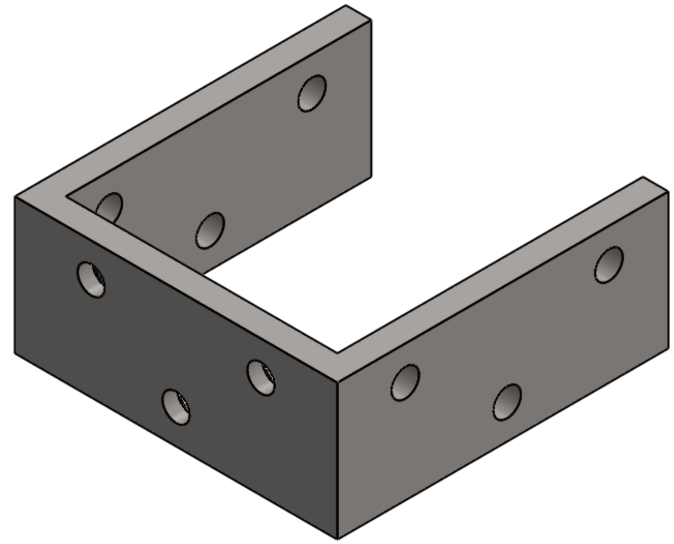
M 3

TITLE:
POST TOP

SIZE: A | DWG. NO. 00053 | REV 01

SCALE: 1:1 | SHEET 1 OF 1





ISOMETRIC VIEW NOT TO SCALE

TAB	DESCRIPTION	REV
00054-01	TOP END	01

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

MATERIAL
AISI 304

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

DO NOT SCALE DRAWING

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

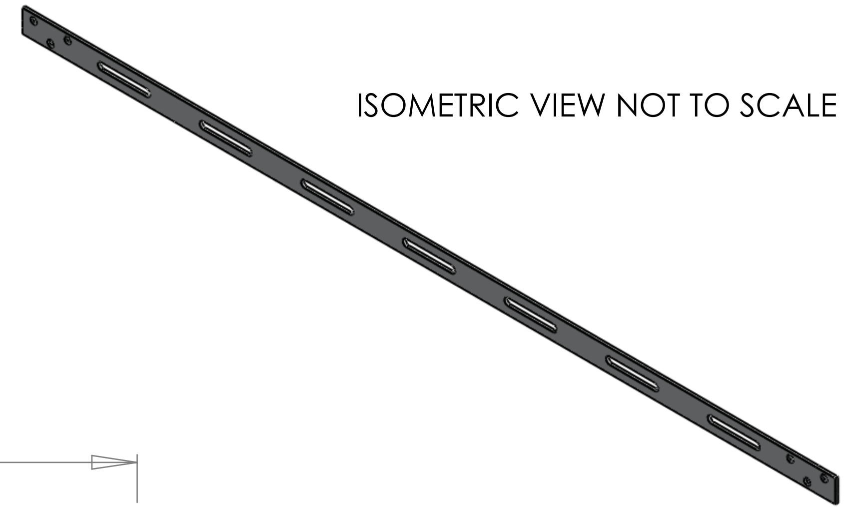
M^3

TITLE:
TOP END

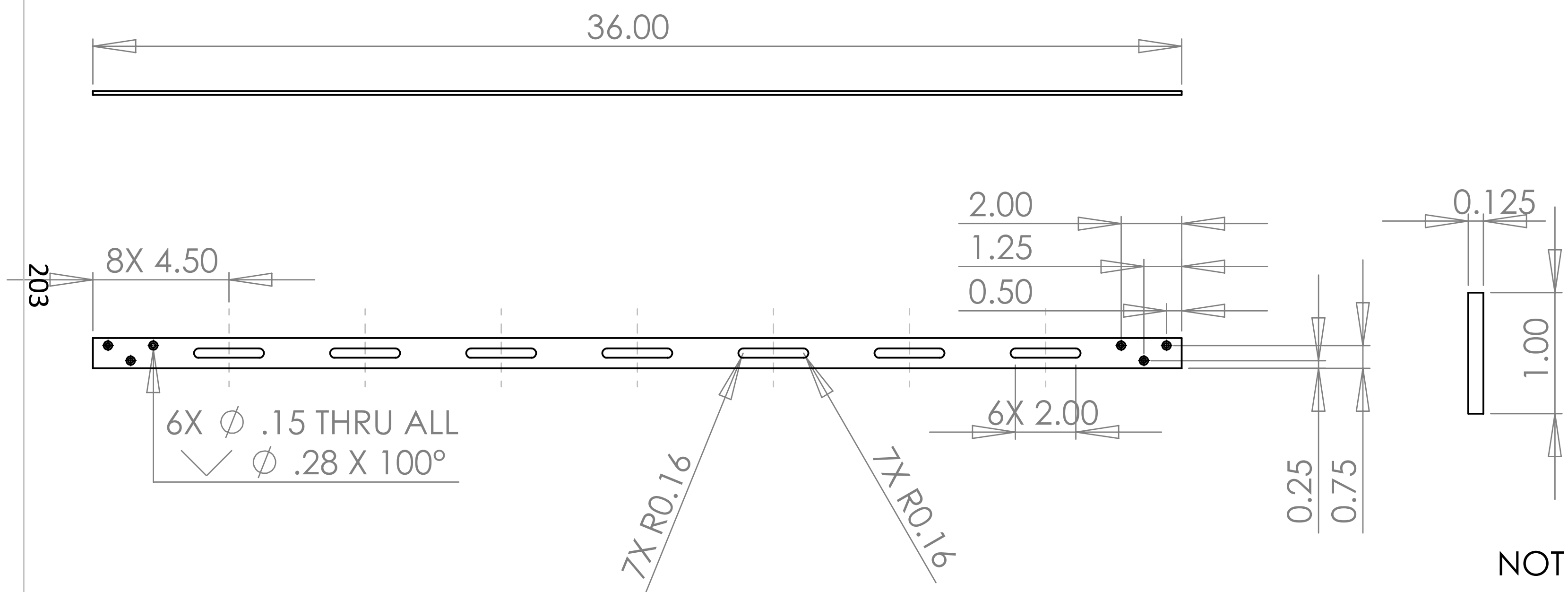
SIZE A | DWG. NO. 00054 | REV 01

SCALE: 1:1 | SHEET 1 OF 1

TAB	DESCRIPTION	REV
00055-01	TOP RAIL	01



ISOMETRIC VIEW NOT TO SCALE



SIDE VIEW
NOT TO SHEET SCALE
2:3

UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	APPROVALS	NAME	DATE
INCH STANDARD TOLERANCES: .X ± .1 .XX ± .01 .XXX ± .005 .XXXX ± .0005	DRAWN	ALI NASH	18 MAR 2013
	CHECKED	ALI NASH	18 MAR 2013
	ENGINEER	ALEX ZATOPA	18 MAR 2013
	DESIGNER	ALEX ZATOPA	18 MAR 2013
ANGLES ± 1 DEGREE	UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.		
MATERIAL 6061 ALLOY			
FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT) N/A			
DO NOT SCALE DRAWING			

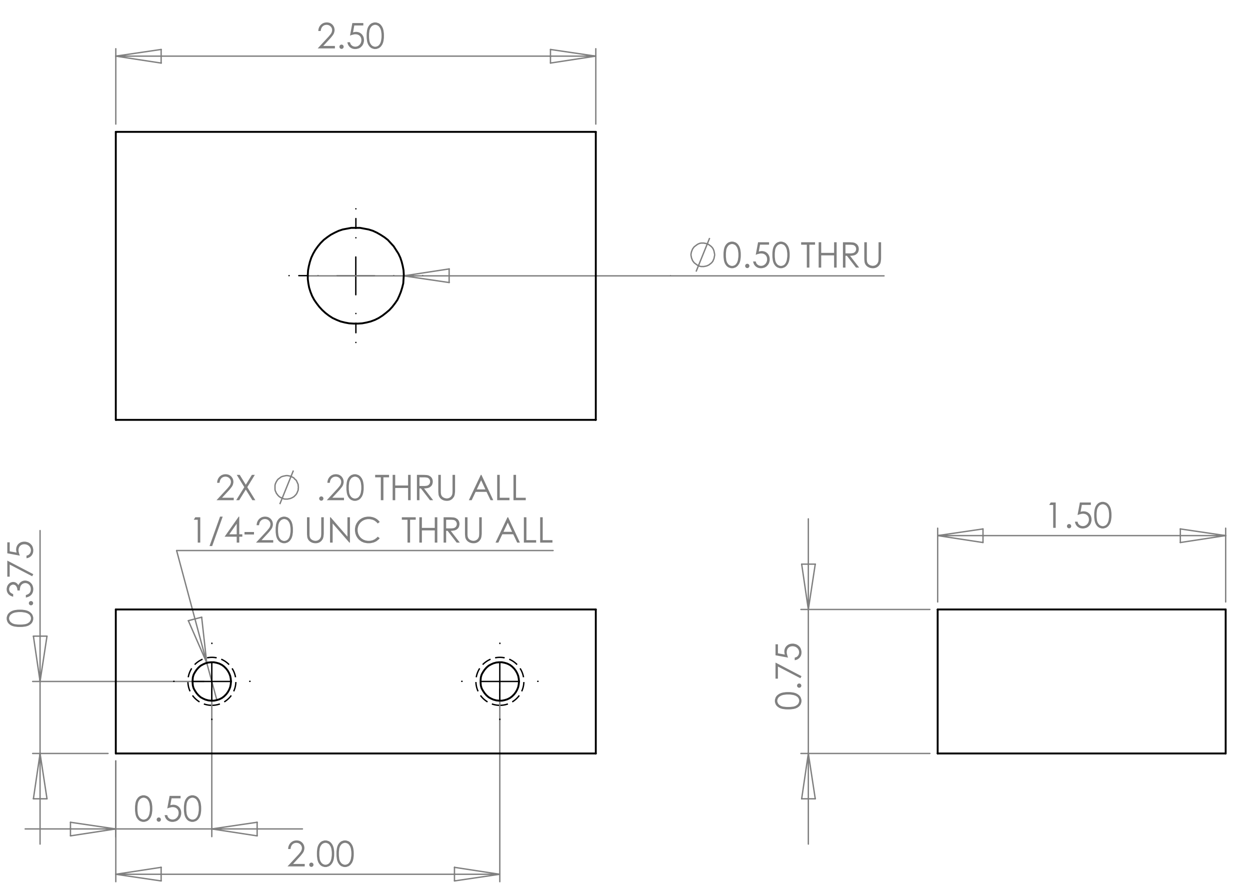
M 3

TITLE:

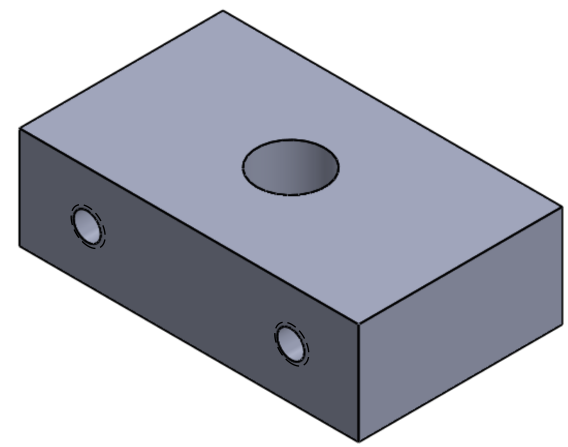
TOP RAIL

SIZE	DWG. NO.	REV
A	00055	01
SCALE: 1:6		SHEET 1 OF 1

TAB	DESCRIPTION	REV
00056-01	TOP BLOCK	01



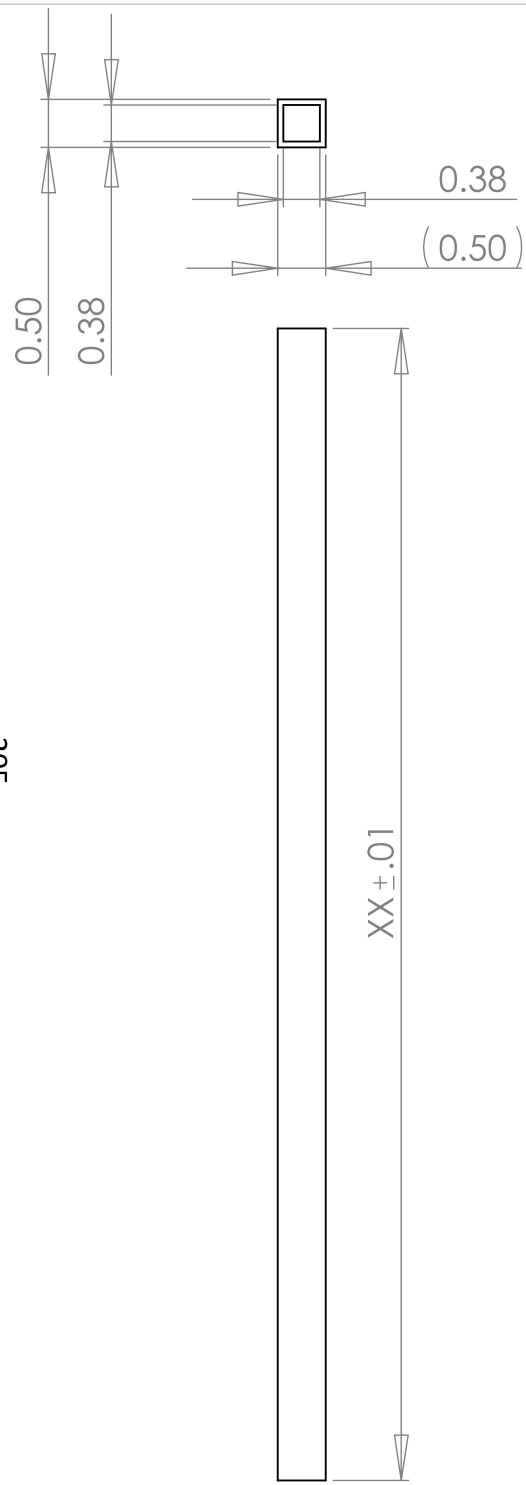
ISOMETRIC VIEW NOT TO SCALE

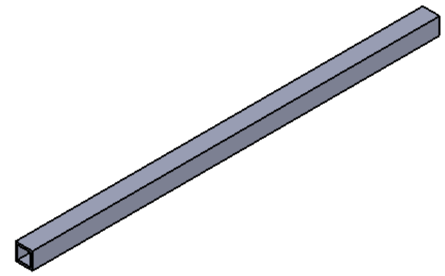


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	APPROVALS	NAME	DATE
INCH STANDARD TOLERANCES: .X ± .1 .XX ± .01 .XXX ± .005 .XXXX ± .0005	DRAWN	ALI NASH	18 MAR 2013
	CHECKED	ALI NASH	18 MAR 2013
	ENGINEER	ALEX ZATOPA	18 MAR 2013
	DESIGNER	ALEX ZATOPA	18 MAR 2013
ANGLES ± 1 DEGREE	UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.		
MATERIAL DELRIN 2700 NC010			
FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT) N/A			
DO NOT SCALE DRAWING			

M[3]

TITLE:	TOP BLOCK	
SIZE **A**	DWG. NO. 00056	REV 01
SCALE: 1:1		SHEET 1 OF 1





ISOMETRIC VIEW NOT TO SCALE

TAB	XX (INCHES)	REV
00057-01	36.00	01
00057-02	2.45	01
00057-03	2.00	01
00057-04	6.00	01
00057-05	8.646	01
00057-06	10.375	01
00057-07	7.925	01
00057-08	35.00	01
00057-09	15.80	01
00057-10	4.00	01
00057-11	2.146	01
00057-12	30.00	01
00057-13	16.20	01

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:
.X ± .1
.XX ± .01
.XXX ± .005
.XXXX ± .0005

ANGLES ± 1 DEGREE

MATERIAL
A513 STEEL

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

DO NOT SCALE DRAWING

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

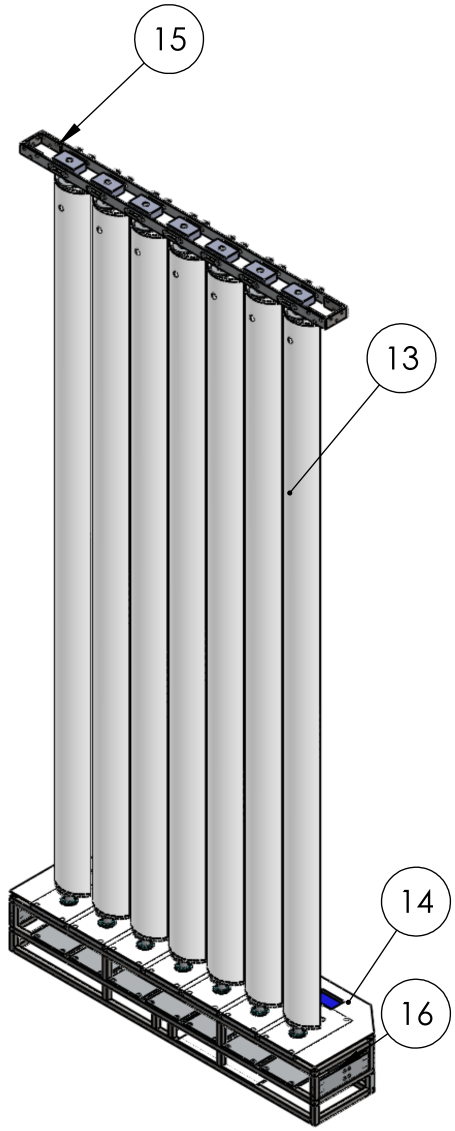
M 3

TITLE:
STEEL TUBE

SIZE A | DWG. NO. 00057 | REV 01

SCALE: 1:4 | SHEET 1 OF 1

Chapter A.15: Assembly Drawings



ITEM NO.	DESCRIPTION	MANUFACTURER	PART NUMBER	QTY.
1	316 SS FH PH SCR 6-32 x 1/2"	MCMASTER-CARR	91500A148	25
2	No. 10 #2 Drive x 2.5"	MCMASTER-CARR	90184A409	6
3	18-8 SS FH PH 10-24 SCR x 1.25"	MCMASTER-CARR	91500A249	54
4	18-8 SS FH PH 10-24 SCR x 1.75"	MCMASTER-CARR	91771A254	2
5	18-8 SS FH PH 10-24 SCR x 1"	MCMASTER-CARR	91500A247	8
6	18-8 SS FH PH 6-32 SCR x 1.5"	MCMASTER-CARR	91771A157	8
7	18-8 SS FH PH 8-32 SCR x 2"	MCMASTER-CARR	91771A205	8
8	18-8 SS FH PH 5-40 SCR x 1"	MCMASTER-CARR	91793A133	6
9	TI Hex Nut 6-32 x 5/16" W x 7/64" H	MCMASTER-CARR	90545A007	25
10	TI Hex Nut 10-24 x 3/8" W x 1/8" H	MCMASTER-CARR	90545A011	56
11	ZN-Pltd Steel Hex Nut 8-32 x 11/32" W x 1/8" H	MCMASTER-CARR	90480A009	8
12	ZN-Pltd Grade 2 STL Nylon-Insert Hex Locknut 5-40 x 1/4" W x 9/64" H	MCMASTER-CARR	90631A006	6
13	LOUVER ASSY	N/A	M0002-01	7
14	BASE ASSY	N/A	M0004-01	1
15	TOP ASSY	N/A	M0006-01	1
16	BEARING ASSY	N/A	M0005-01	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

MATERIAL
SEE BOM

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

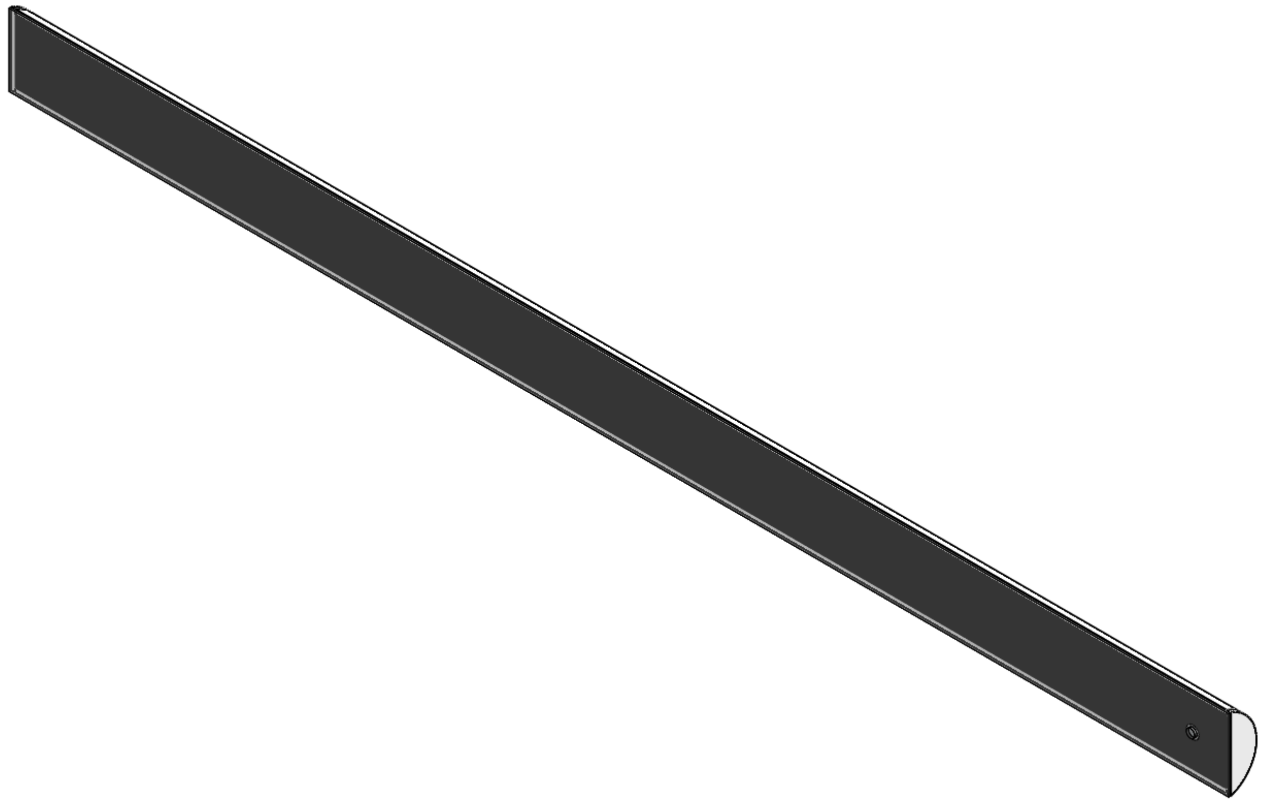
DO NOT SCALE DRAWING

M 3

TITLE:
BLINDS FINAL ASSY

SIZE	DWG. NO.	REV
A	FG0001	01

SCALE: 1:16 SHEET 1 OF 1



ITEM NO.	DESCRIPTION	MANUFACTURER	PART NUMBER	QTY.
1	LOUVER BACK	N/A	00011-01	1
2	LOUVER FACE	N/A	00012-01	1
3	END CAP	N/A	00013-01	2
4	FOIL TAPE	MCMASTER-CARR	76055A23	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

MATERIAL
SEE BOM

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

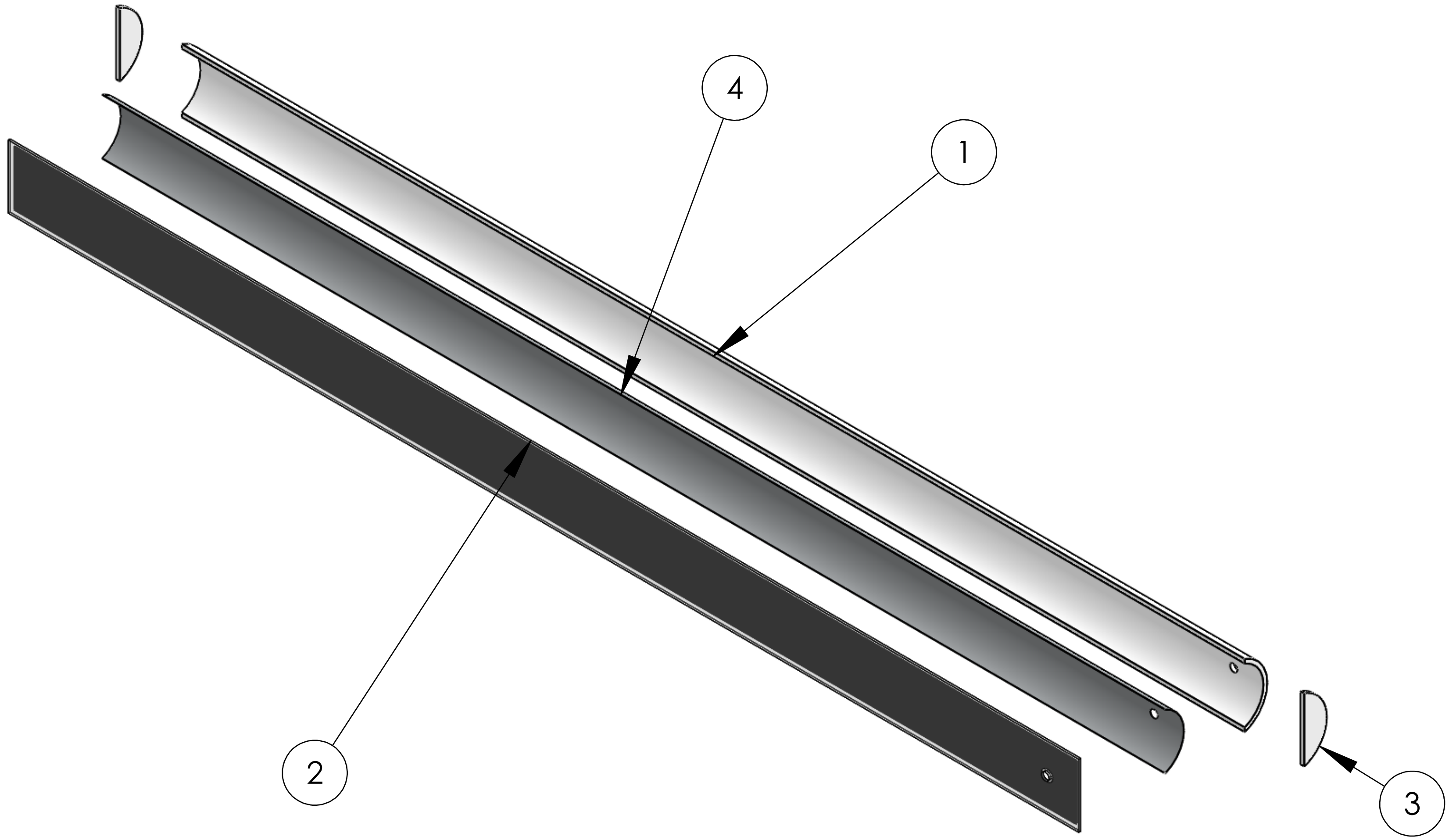
DO NOT SCALE DRAWING

M[3]

TITLE:
LOUVER ASSY

SIZE A | DWG. NO. M0002 | REV 01

SCALE: 1:8 | SHEET 1 OF 2



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

MATERIAL
SEE BOM

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

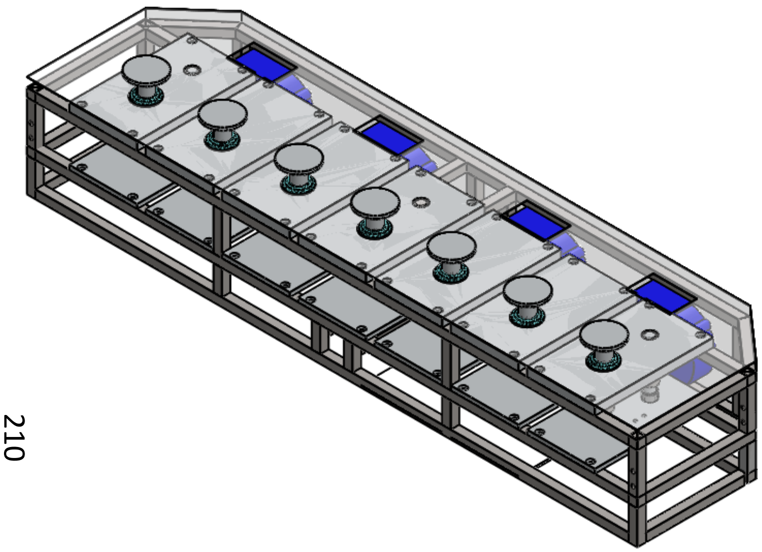
DO NOT SCALE DRAWING

M 3

TITLE:
LOUVER ASSY

SIZE A | DWG. NO. M0002 | REV 01

SCALE: 1:8 | SHEET 2 OF 2



ITEM NO.	DESCRIPTION	MANUFACTURER	PART NUMBER	QTY.
1	WELDED FRAME ASSY	N/A	00041-01	1
2	SUPPORT SHEET TOP	N/A	00039-01	4
3	SUPPORT SHEET BOTTOM	N/A	00035-01	4
4	SUPPORT SHEET TOP EDGE	N/A	00044-01	3
5	SUPPORT SHEET EDGE BOTTOM	N/A	00036-01	2
6	Steel Needle-Roller Bearing 1/2" ID	MCMASTER-CARR	5905K23	12
7	Steel Tapered-Roller Bearing 1/2" ID	MCMASTER-CARR	23915T11	7
8	POST BOTTOM	N/A	00029-01	7
9	WORM GEAR	MCMASTER-CARR	5172721	10
10	DRIVE ROD	N/A	00028-01	1
11	SERVO	SERVO-CITY	HS-5685HB	1
12	FAN	NIDEC AMERICA	A35683	4
13	END POST	N/A	00047-01	2
14	SPACER	N/A	00050-01	2
15	SUPPORT SHEET MIDDLE BOTTOM	N/A	00037-01	1
16	TOP SHEET	N/A	00040-01	1
17	PVC PLATE	N/A	00052-01	1
18	FRONT COVER	N/A	00048-01	1
19	PRESS PIN	MCMASTER-CARR	99010A127	10

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:
.X ± .1
.XX ± .01
.XXX ± .005
.XXXX ± .0005

ANGLES ± 1 DEGREE

MATERIAL
SEE BOM

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

DO NOT SCALE DRAWING

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

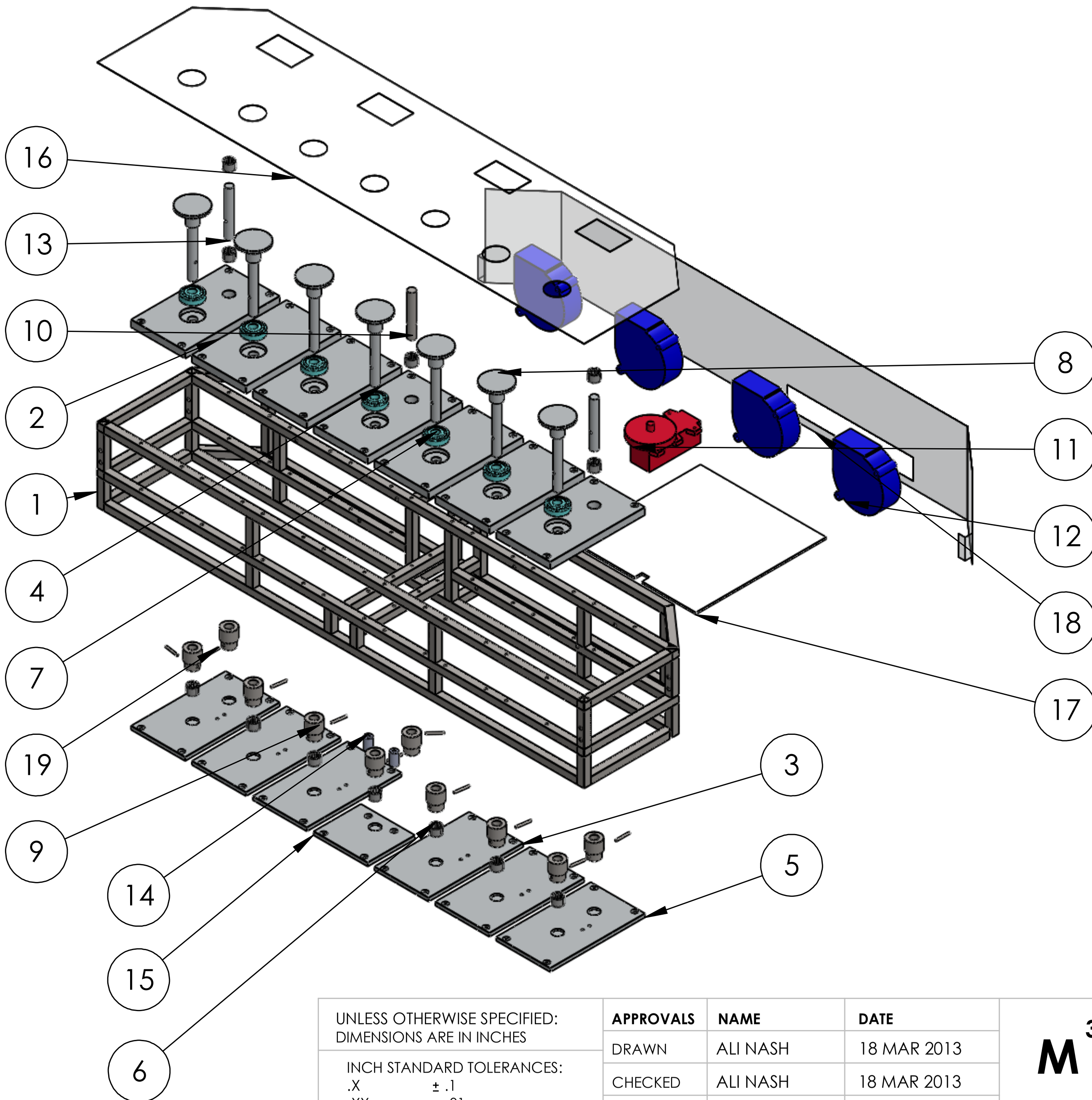
UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

M 3

TITLE:
BASE ASSY

SIZE A | DWG. NO. M0004 | REV 01

SCALE: 1:8 | SHEET 1 OF 2



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

MATERIAL
SEE BOM

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

DO NOT SCALE DRAWING

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

M^3

TITLE:
BASE ASSY

SIZE A | DWG. NO. M0004 | REV 01

SCALE: 1:9 | SHEET 2 OF 2

ITEM NO.	DESCRIPTION	MANUFACTURER	PART NUMBER	QTY.
1	RACK	MCMASTER-CARR	5174T22	2
2	RACK SUPPORT	N/A	00030-01	1
3	BEARING SUPPORT	N/A	00045-01	2
4	BEARING SUPPORT ROD	N/A	00046-01	7
5	Steel Ball Bearing Plain Open 3/16" ID	MCMASTER-CARR	6383K11	7
6	END SUPPORT	N/A	00051-01	2

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

MATERIAL
SEE BOM

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

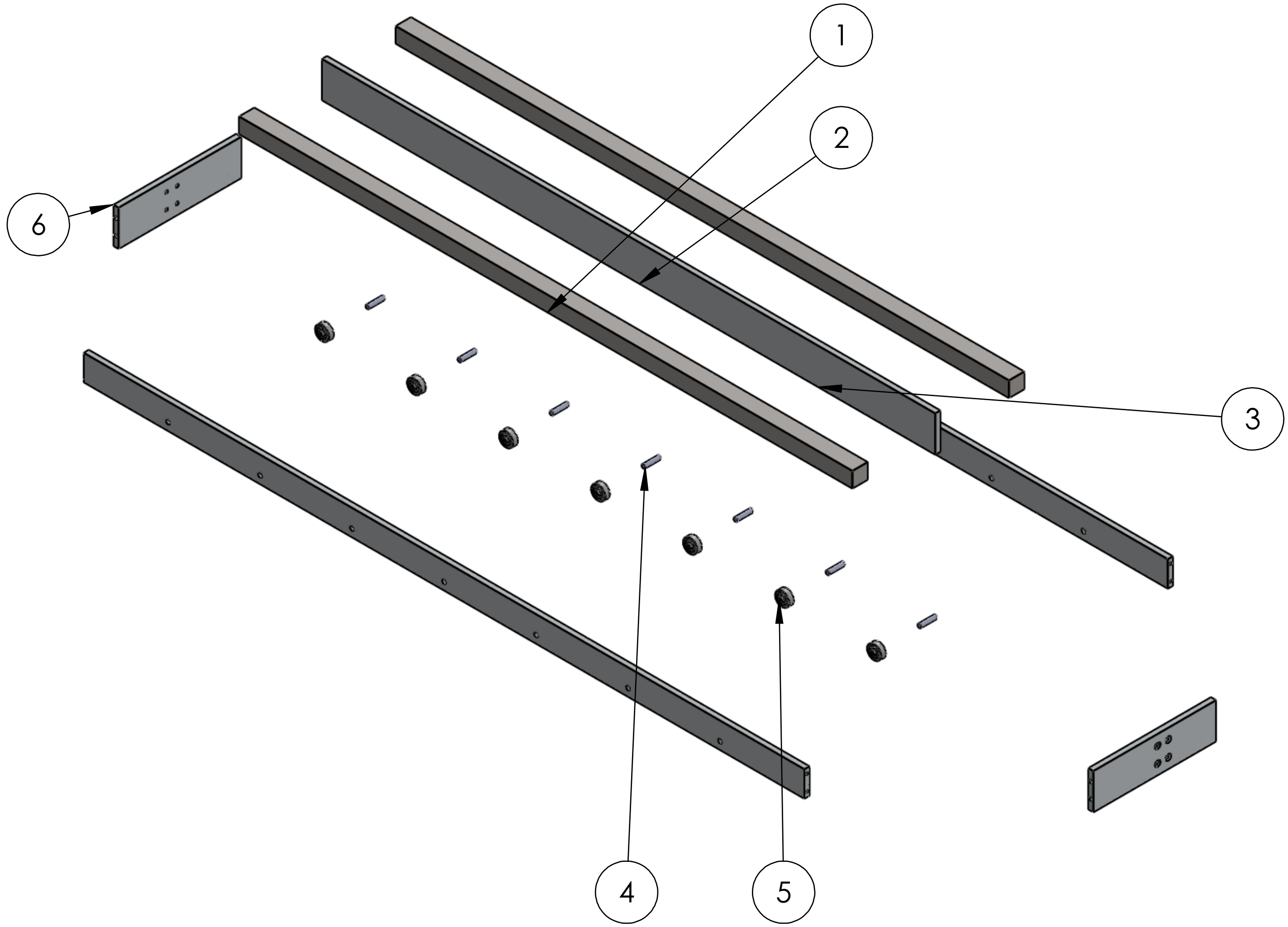
DO NOT SCALE DRAWING

M^3

TITLE:
BEARING ASSY

SIZE	DWG. NO.	REV
A	M0005	01

SCALE: 1:6 | SHEET 1 OF 2



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	APPROVALS	NAME	DATE
INCH STANDARD TOLERANCES: .X ± .1 .XX ± .01 .XXX ± .005 .XXXX ± .0005	DRAWN	ALI NASH	18 MAR 2013
	CHECKED	ALI NASH	18 MAR 2013
	ENGINEER	ALEX ZATOPA	18 MAR 2013
	DESIGNER	ALEX ZATOPA	18 MAR 2013
ANGLES ± 1 DEGREE	UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.		
MATERIAL SEE BOM			
FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT) N/A			
DO NOT SCALE DRAWING			

M[3]

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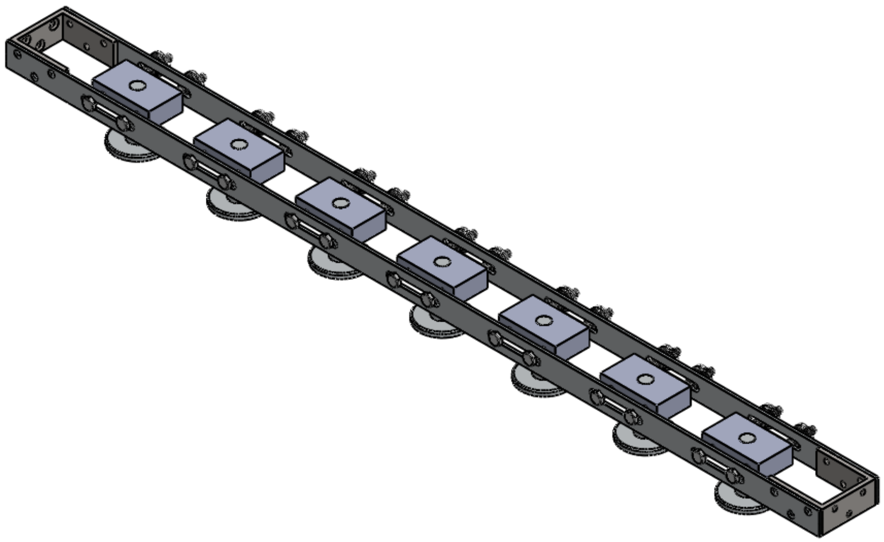
TITLE:
BEARING ASSY

SIZE	DWG. NO.	REV
A	M0005	01
SCALE: 1:6		SHEET 2 OF 2



ITEM NO.	DESCRIPTION	MANUFACTURER	PART NUMBER	QTY.
1	POST TOP	N/A	00053-01	7
2	TOP END	N/A	00054-01	2
3	TOP RAIL	N/A	00055-01	2
4	TOP BLOCK	N/A	00056-01	7
5	Steel Hex Head Cap Screws	MCMASTER-CARR	92865A556	14
6	Round Knurled Thumb Nut	MCMASTER-CARR	91833A134	14

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

MATERIAL
SEE BOM

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

DO NOT SCALE DRAWING

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

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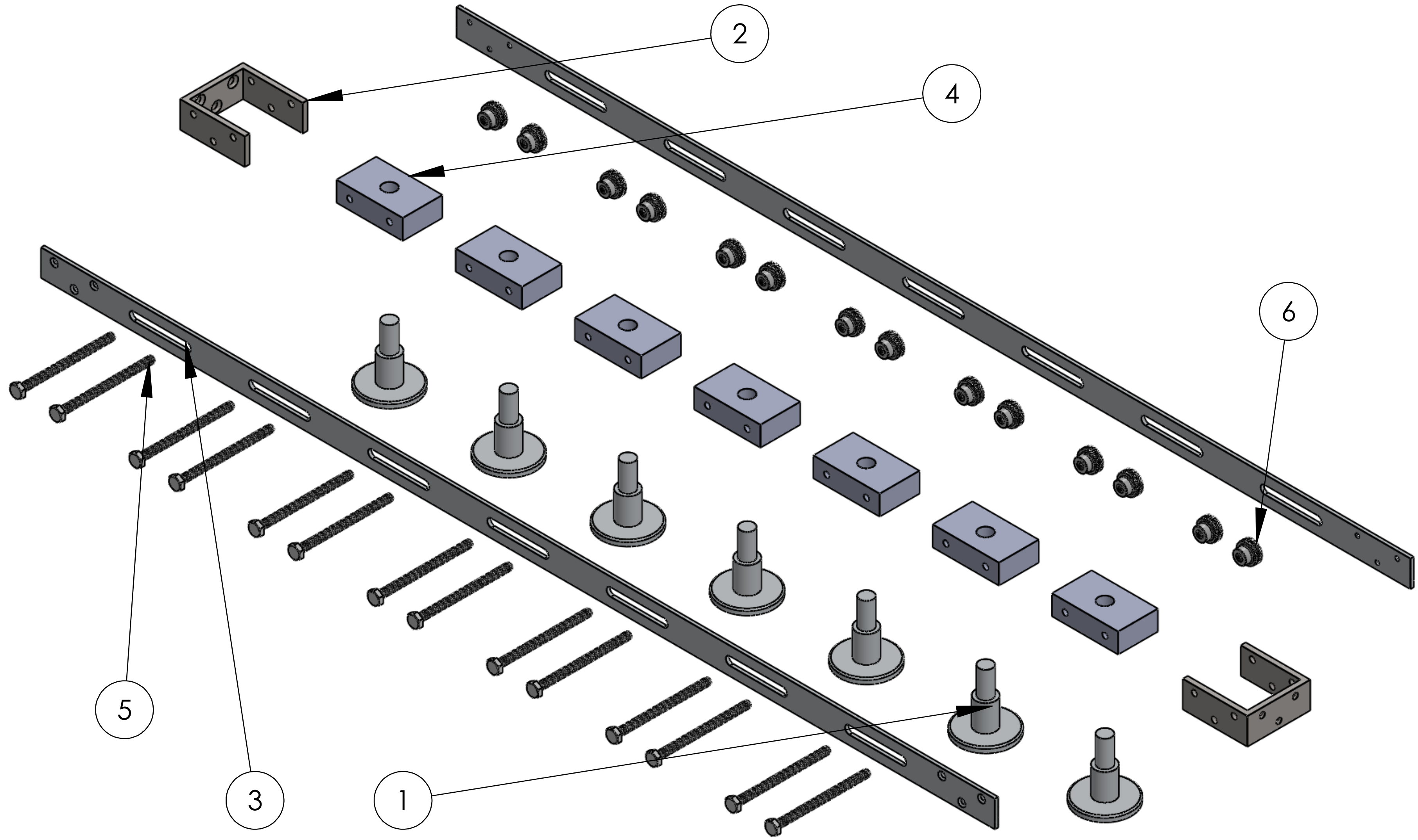
M 3

TITLE:
TOP ASSY

SIZE A | DWG. NO. M0006 | REV 01

SCALE: 1:6 | SHEET 1 OF 2

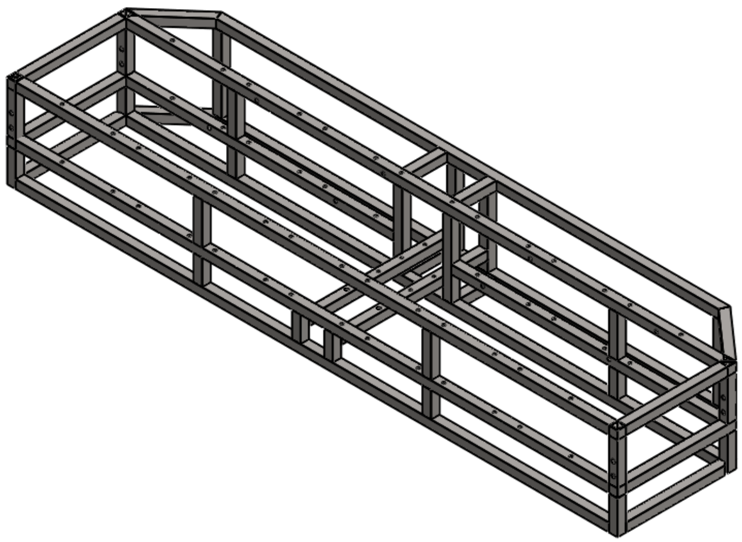


UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	APPROVALS	NAME	DATE
INCH STANDARD TOLERANCES: .X ± .1 .XX ± .01 .XXX ± .005 .XXXX ± .0005	DRAWN	ALI NASH	18 MAR 2013
	CHECKED	ALI NASH	18 MAR 2013
	ENGINEER	ALEX ZATOPA	18 MAR 2013
	DESIGNER	ALEX ZATOPA	18 MAR 2013
ANGLES ± 1 DEGREE	UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.		
MATERIAL SEE BOM			
FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT) N/A			
DO NOT SCALE DRAWING			

M3

TITLE: TOP ASSY

SIZE	DWG. NO.	REV
A	M0006	01
SCALE: 1:4		SHEET 2 OF 2



ITEM NO.	PART NUMBER	DESCRIPTION	LENGTH (INCHES)	QTY.
1	00057-01	STEEL TUBE	36	4
2	00057-02	STEEL TUBE	2.45	8
3	00057-03	STEEL TUBE	2	10
4	00057-04	STEEL TUBE	6	6
5	00057-05	STEEL TUBE	8.646	2
6	00057-06	STEEL TUBE	10.375	4
7	00057-07	STEEL TUBE	7.925	2
8	00057-08	STEEL TUBE	35	1
9	00057-09	STEEL TUBE	15.8	2
10	00057-10	STEEL TUBE	4	4
11	00057-11	STEEL TUBE	2.146	4
12	00057-12	STEEL TUBE	30	2
13	00057-13	STEEL TUBE	16.2	2

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES

INCH STANDARD TOLERANCES:

.X	± .1
.XX	± .01
.XXX	± .005
.XXXX	± .0005

ANGLES ± 1 DEGREE

MATERIAL
SEE BOM

FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT)
N/A

DO NOT SCALE DRAWING

APPROVALS	NAME	DATE
DRAWN	ALI NASH	18 MAR 2013
CHECKED	ALI NASH	18 MAR 2013
ENGINEER	ALEX ZATOPA	18 MAR 2013
DESIGNER	ALEX ZATOPA	18 MAR 2013

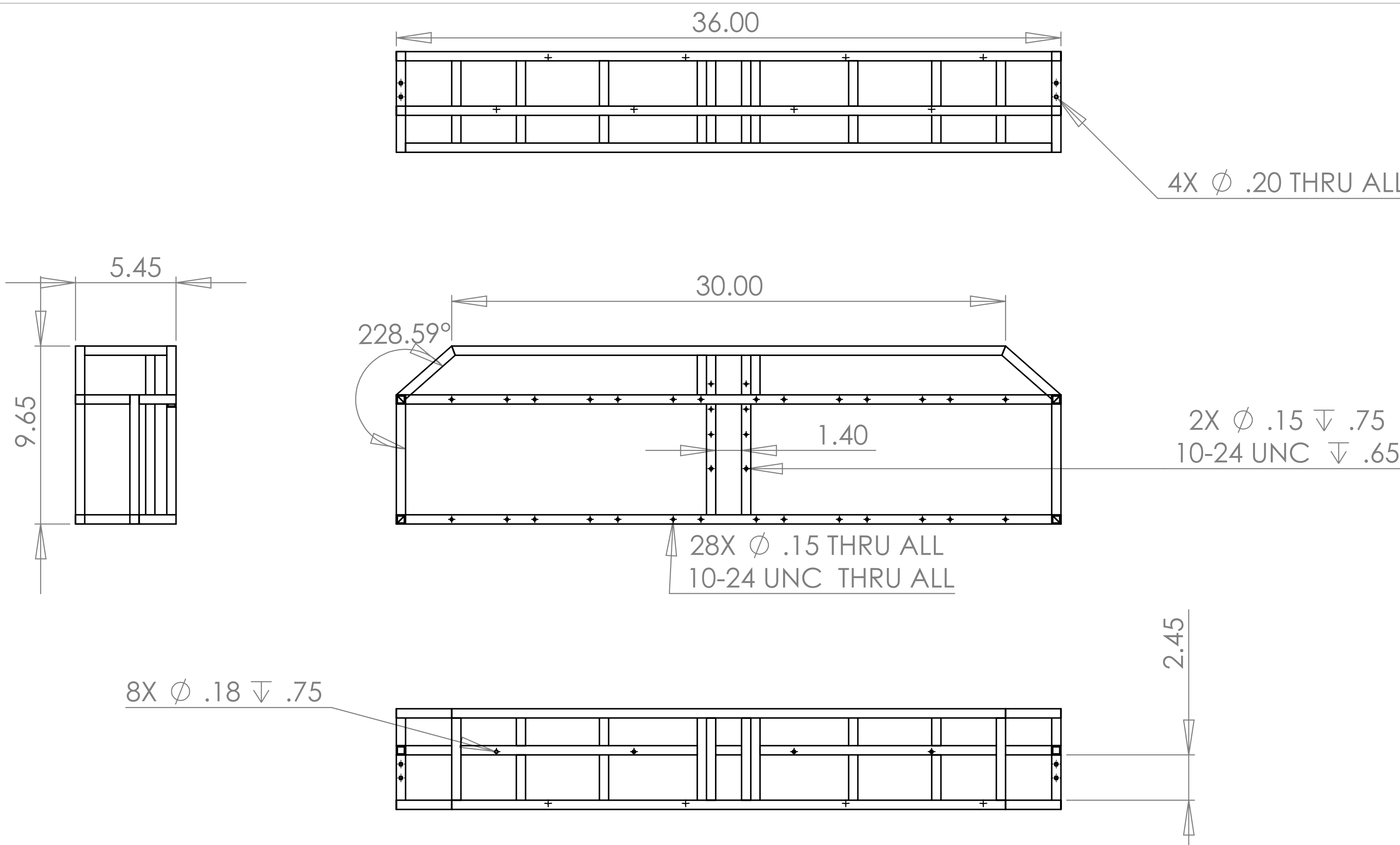
UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.

M 3

TITLE:
WELDED FRAME ASSY

SIZE A | DWG. NO. 00041 | REV 02

SCALE: 1:8 | SHEET 1 OF 2



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES	APPROVALS	NAME	DATE
INCH STANDARD TOLERANCES: .X ± .1; .XX ± .01; .XXX ± .005; .XXXX ± .0005	DRAWN	ALI NASH	18 MAR 2013
	CHECKED	ALI NASH	18 MAR 2013
	ENGINEER	ALEX ZATOPA	18 MAR 2013
	DESIGNER	ALEX ZATOPA	18 MAR 2013
ANGLES ± 1 DEGREE	UNLESS OTHERWISE SPECIFIED, LIMIT DIMENSIONS ARE ABSOLUTE, UNILATERAL AND BILATERAL DIMENSIOONS PERMIT ROUNDING.		
MATERIAL SEE BOM			
FINISH (UNLESS OTHERWISE SPECIFIED DIEMSNIOSN APPLY PRIOR TO TREATMENT) N/A			
DO NOT SCALE DRAWING			

M 3

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TITLE:

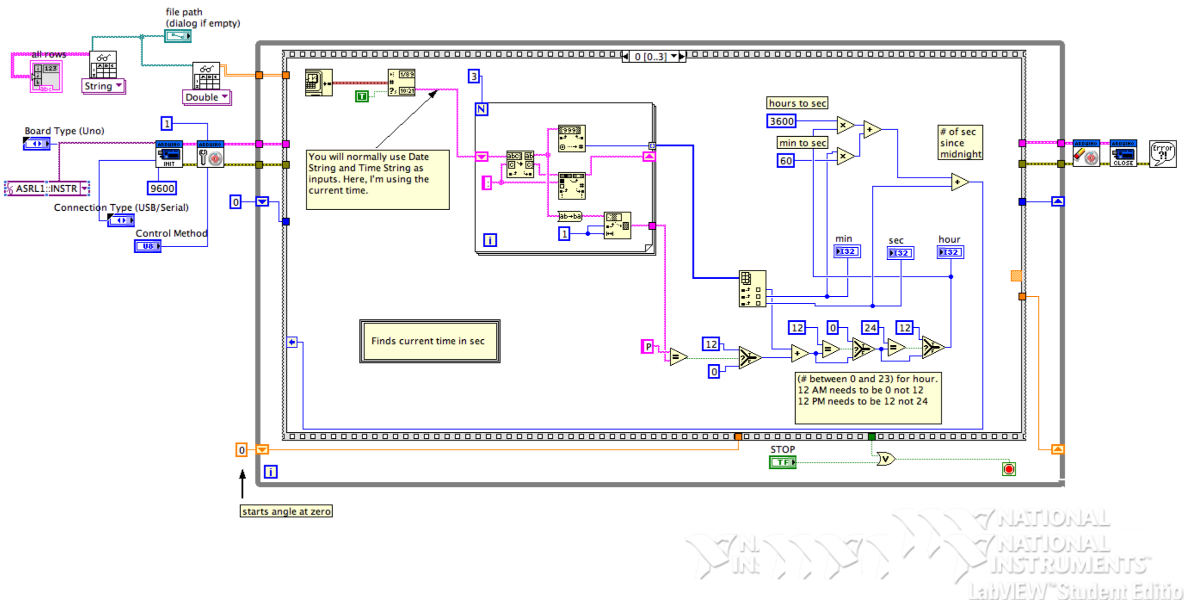
WELDED FRAME ASSY

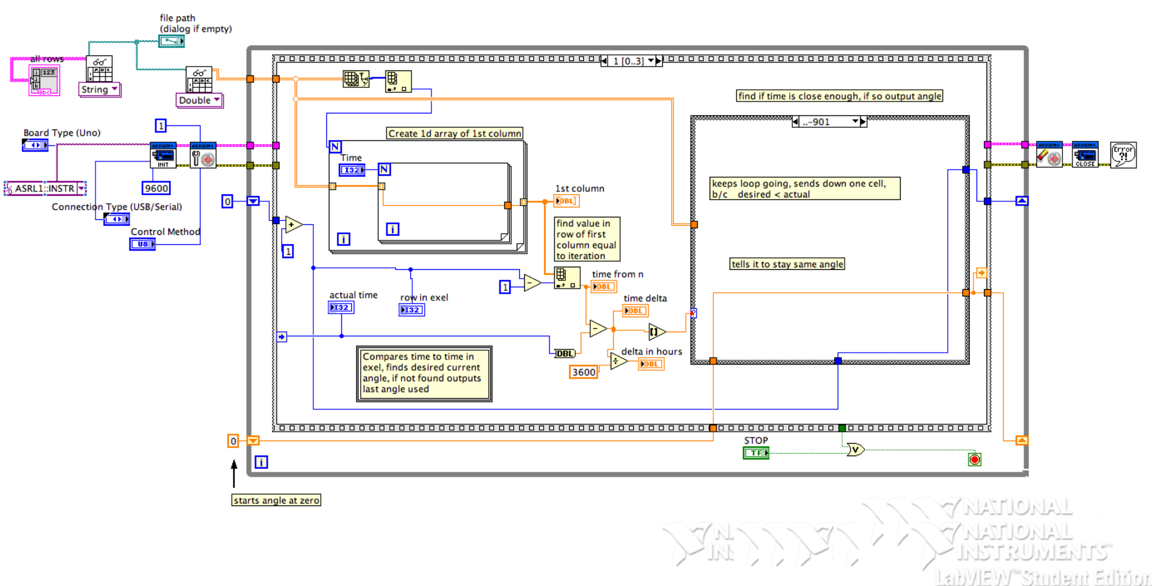
SIZE A | DWG. NO. 00041 | REV 02

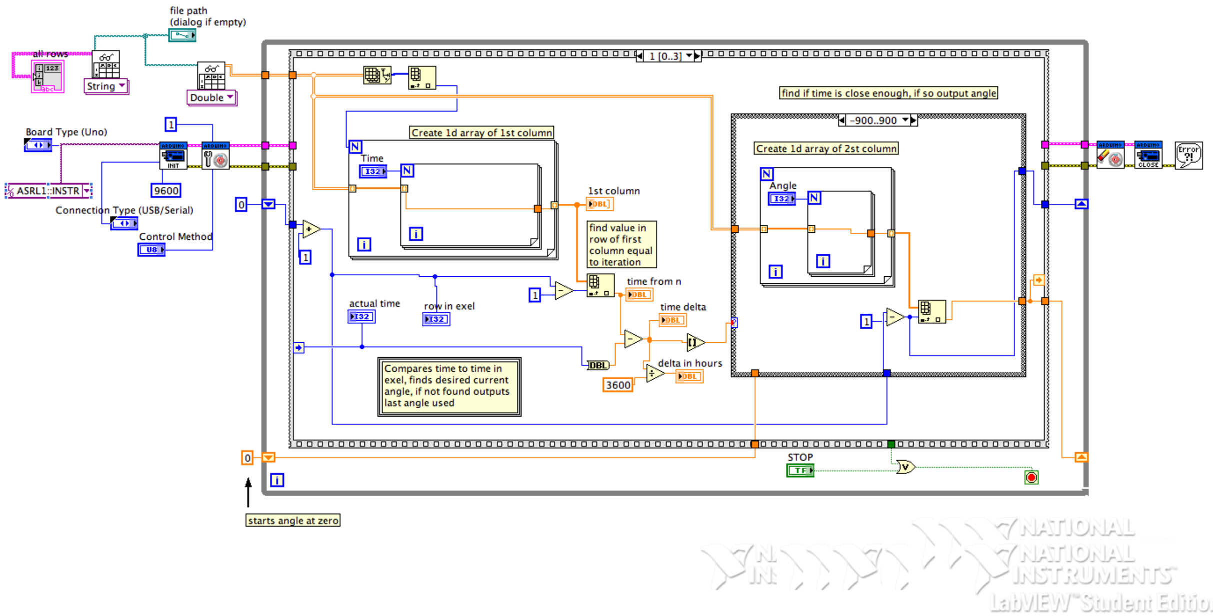
SCALE: 1:8 | SHEET 2 OF 2

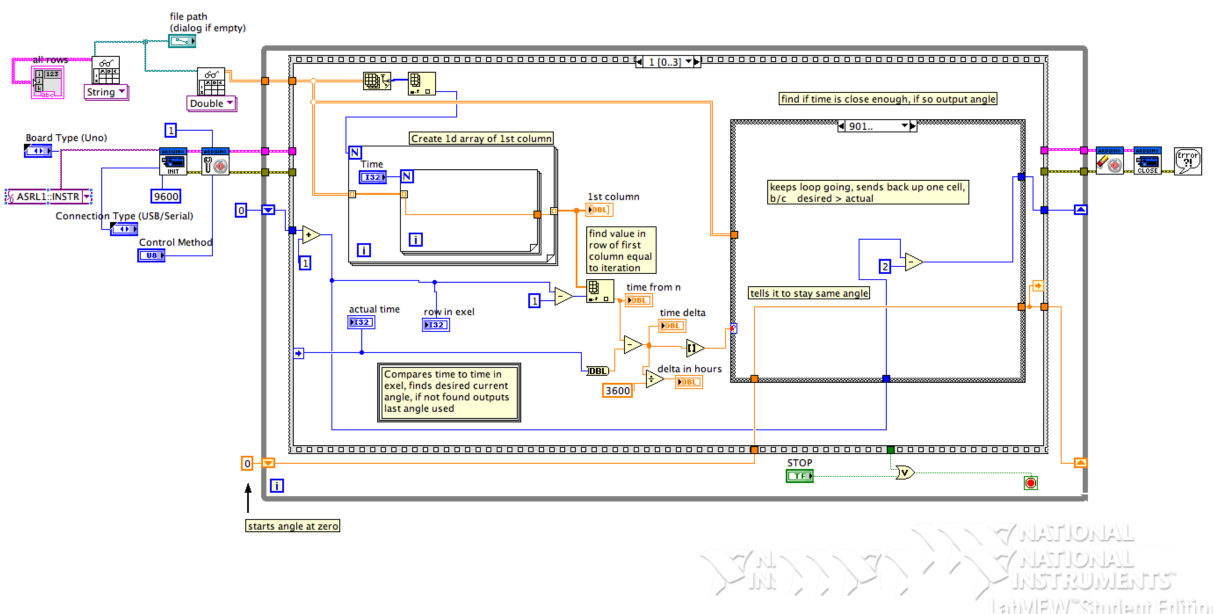
Chapter A.16: Control System Code and Input Data

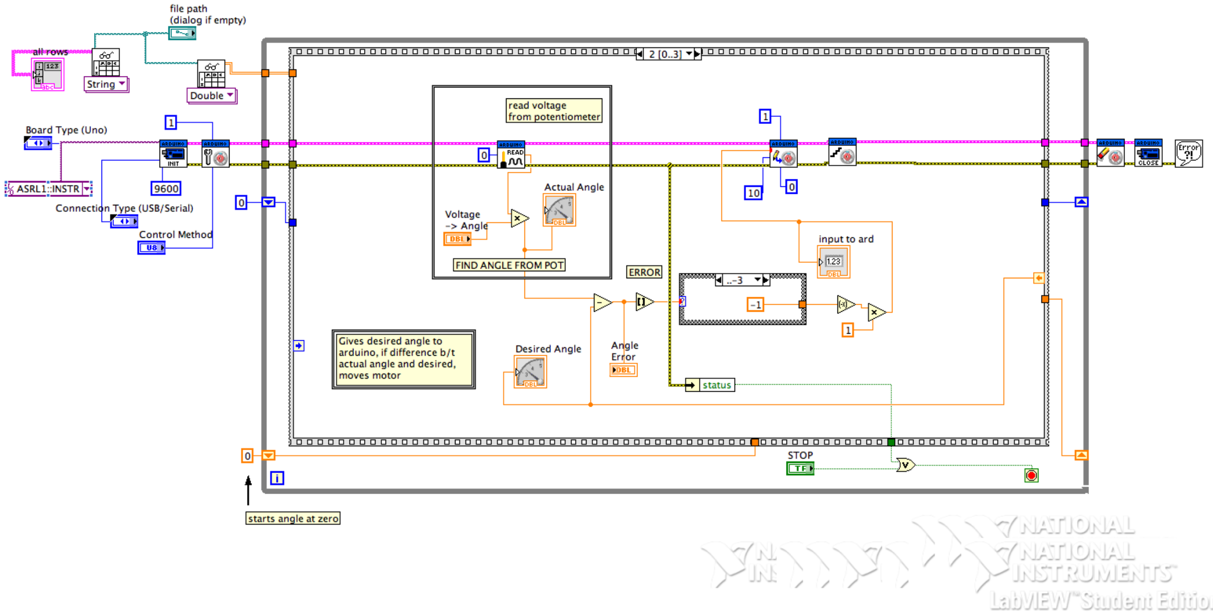
LabView Virtual Instrument (VI) –

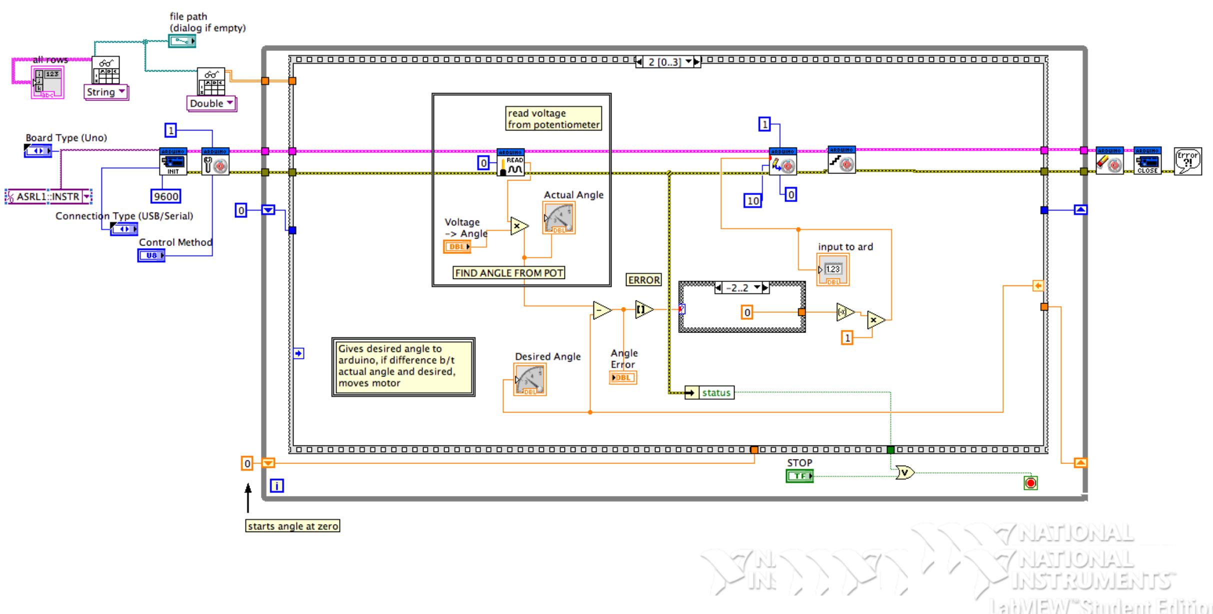


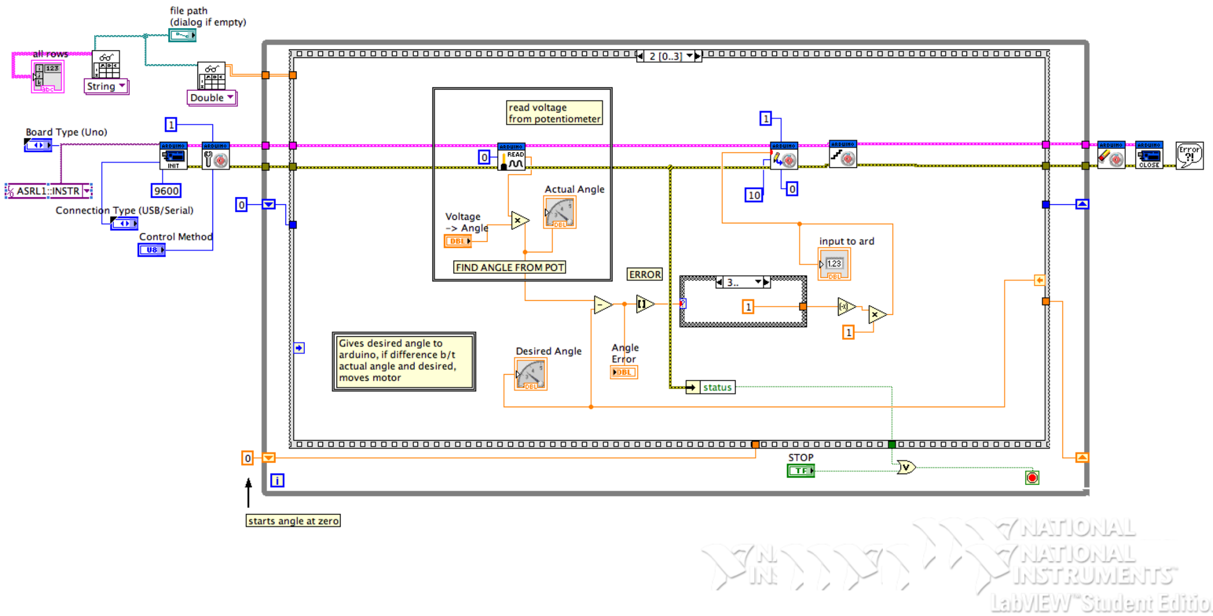


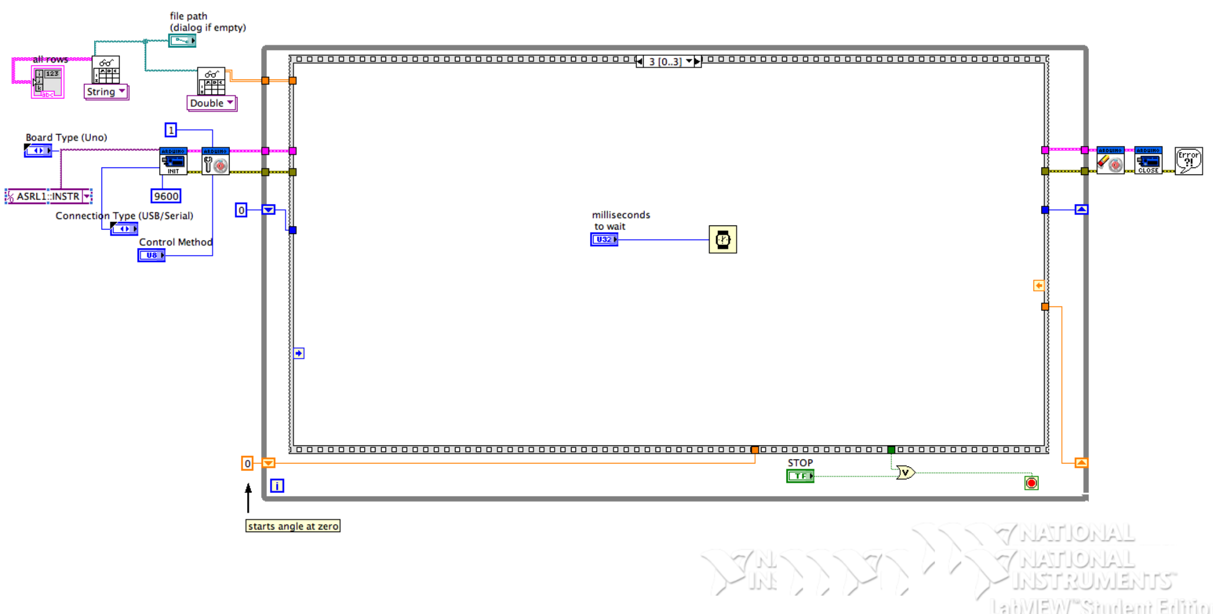

file path
(dialog if empty)
all rows
String
Double
Board Type (Uno)
ASRL1::INSTR
9600
Connection Type (USB/Serial)
Control Method
1 [0..3]
Create 1d array of 1st column
Time
1st column
find value in row of first column equal to iteration
time from n
actual time
row in exel
time delta
delta in hours
3600
Compares time to time in exel, finds desired current angle, if not found outputs last angle used
find if time is close enough, if so output angle
-900..900
Create 1d array of 2st column
Angle
STOP
starts angle at zero
NATIONAL INSTRUMENTS
LabVIEW Student Edition


file path
(dialog if empty)
all rows
String
Double
Board Type (Uno)
ASRL1::INSTR
9600
Connection Type (USB/Serial)
Control Method
1 [0..3]
Create 1d array of 1st column
Time
1st column
find value in row of first column equal to iteration
time from n
actual time
row in exel
time delta
delta in hours
3600
Compares time to time in exel, finds desired current angle, if not found outputs last angle used
find if time is close enough, if so output angle
901..
keeps loop going, sends back up one cell, b/c desired > actual
tells it to stay same angle
STOP
starts angle at zero
NATIONAL INSTRUMENTS
LabVIEW Student Edition


file path
(dialog if empty)
all rows
String
Double
Board Type (Uno)
ASRL1::INSTR
9600
Connection Type (USB/Serial)
Control Method
2 [0..3]
read voltage
from potentiometer
Voltage
-> Angle
Actual Angle
FIND ANGLE FROM POT
ERROR
..-3
-1
input to ard
Gives desired angle to
arduino, if difference b/t
actual angle and desired,
moves motor
Desired Angle
Angle
Error
status
STOP
starts angle at zero
NATIONAL INSTRUMENTS
LabVIEW Student Edition


file path
(dialog if empty)
all rows
String
Double
Board Type (Uno)
ASRL1::INSTR
9600
Connection Type (USB/Serial)
Control Method
2 [0..3]
read voltage
from potentiometer
Voltage
-> Angle
Actual Angle
FIND ANGLE FROM POT
ERROR
-2..2
input to ard
Gives desired angle to
arduino, if difference b/t
actual angle and desired,
moves motor
Desired Angle
Angle
Error
status
STOP
starts angle at zero
NATIONAL INSTRUMENTS
LabVIEW Student Edition


file path
(dialog if empty)
all rows
String
Double
Board Type (Uno)
ASRL1::INSTR
Connection Type (USB/Serial)
Control Method
9600
2 [0..3]
read voltage
from potentiometer
Actual Angle
Voltage
-> Angle
FIND ANGLE FROM POT
ERROR
input to ard
Gives desired angle to
arduino, if difference b/t
actual angle and desired,
moves motor
Desired Angle
Angle
Error
status
STOP
starts angle at zero
NATIONAL INSTRUMENTS
LabVIEW Student Edition


file path
(dialog if empty)
all rows
String
Double
Board Type (Uno)
ASRL1::INSTR
Connection Type (USB/Serial)
Control Method
9600
3 [0..3]
milliseconds
to wait
STOP
starts angle at zero
NATIONAL INSTRUMENTS
LabVIEW Student Edition

Arduino MicroController Sketch

```
/*
  Alex Zatopa 6/2/2013
  Senior Design Control System

  Utilizes predesigned sketches for compass and clock. Original code and libraries can be found at:

    Compass: https://github.com/pololu/LSM303
    Clock: http://bildr.org/2011/03/ds1307-arduino/


*/

// libraries
#include <math.h>
#include <Servo.h>
#include <Wire.h>
#include <LSM303.h>

// create objects
Servo myservo;
LSM303 compass;

// constant definitions
#define DS1307_ADDRESS 0x68
#define TIMEANGLEROWS 113
#define TIMEANGLECOLUMNS 2
#define SERVOPIN 9

// global variables

double angle;
long i = 0;
long currentcell = 0;
double timeinsec;
int timeerror = 1000;
double servoangle;
int heading;
byte zero = 0x00;



// setup ----------------------------------------------
void setup()
{
  Wire.begin();
  Serial.begin(9600);

 // setDateTime();  // uncomment if the time is to be reset

  //for compass
```

```
  compass.init();
  compass.enableDefault();

  // Calibration values. Use the Calibrate example program to get the values for
  // your compass.
  compass.m_min.x = -759; compass.m_min.y = -498; compass.m_min.z = -380;
  compass.m_max.x = +91; compass.m_max.y = +394; compass.m_max.z = 379;

  // initiate pins
  myservo.attach(SERVOPIN);

  // find ref direction
  compass.read();
  heading = compass.heading((LSM303::vector){0,-1,0});
}

// loop ------------------------------------------------
void loop()
{

// initialize time and angle array  --------------------------
double    timeangle [TIMEANGLEROWS] [TIMEANGLECOLUMNS]  = {
{14400, 120},
{15000,  120},
{15600,  120},
{16200,  120},
{16800,  120}, //68.1},
{17400,  120}, //69.7},
{18000,  120}, //71.4},
{18600,  120}, //72.9},
{19200,  120}, //74.5},
{19800,  120}, //76.1},
{20400,  120}, //77.6},
{21000,  120}, //79.1},
{21600,  120}, //80.6},
{22200,  120}, //82.1},
{22800,  120}, //83.6},
{23400,  120}, //85.1},
{24000,  120}, //86.6},
{24600,  120}, //88.1},
{25200,  120}, //89.7},
{25800,  120}, //91.2},
{26400,  120}, //92.8},
{27000,  120}, //94.3},
{27600,  120}, //95.9},
{28200,  120}, //97.6},
{28800,  120}, //99.2},
{29400,  120}, //101},
{30000,  120}, //102.7},
{30600,  120}, //104.6},
{31200,  120}, //106.5},
{31800,  120}, //108.4},
{33000,  120}, //112.6},
```

```
{33600,  120}, //114.9},
{34200,  120}, //117.2},
{34800,  120}, //119.7},
{35400,  122.3},
{36000,  125.1},
{36600,  128.1},
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{42000,  164.6},
{42600,  169.7},
{43200,  174.9},
{43800,  180.2},
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```

```
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{67200,  282.6},
{67800,  284.2},
{68400,  285.7},
{69000,  287.3},
{69600,  288.9},
{70200,  290.6},
{70800,  292.2},
{71400,  120},
{72000,  120},
{72600,  120},
{73200,  120},
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{77400,  120},
{78000,  120},
{78600,  120},
{79200,  120},
{79800,  120},
{80400,  120},
{81000,  120},
{81600,  120},
{82200,  120},
{82800,  120},
{83400,  120}
};
//--------------------------------------------------------
  // get current time
  timeinsec = printDate();


  // compare current time to time in array timeangle to find angle for current time

  while(timeerror > 301 || timeerror < -301)
  {
   if(i<TIMEANGLEROWS)
   {
     timeerror = timeinsec - timeangle[i][0];
     i++;
   }
   else
   {
     timeerror = 1000;
     i = 0;
     break;
   }
  }

  currentcell = i-1;
```

```
  angle = timeangle[i-1][1];  // ANGLE OUTPUT FOR DESIRED TIME


  // find desired angle for servo
  servoangle = angle - heading;

  if(servoangle < 0 )
  {
    servoangle = servoangle + 360;
  }


  // write angle to servo
  double setservo = map(servoangle, 0, 180, 10, 160);
  myservo.write(setservo);

  timeerror = timeinsec - timeangle[currentcell][0];

}

// functions -------------------------------------------

// time functions
byte decToBcd(byte val){
// Convert normal decimal numbers to binary coded decimal
  return ( (val/10*16) + (val%10) );
}
//-------------------

byte bcdToDec(byte val)  {
// Convert binary coded decimal to normal decimal numbers
  return ( (val/16*10) + (val%16) );
}

// function that prints the time in seconds since midnight
unsigned long printDate(){

  // Reset the register pointer
  Wire.beginTransmission(DS1307_ADDRESS);

  byte zero = 0x00;
  Wire.write(zero);
  Wire.endTransmission();

  Wire.requestFrom(DS1307_ADDRESS, 7);

  int second = bcdToDec(Wire.read());
  int minute = bcdToDec(Wire.read());
  int hour = bcdToDec(Wire.read() & 0b111111); //24 hour time
  int weekDay = bcdToDec(Wire.read()); //0-6 -> sunday - Saturday
  int monthDay = bcdToDec(Wire.read());
  int month = bcdToDec(Wire.read());
```

```
  int year = bcdToDec(Wire.read());

unsigned long timeinsec = (unsigned long) second + (unsigned long) minute*60 + (unsigned long) hour*3600;

// returns the time in seconds since midnight
return(timeinsec);
}

//------------------------------------------
// set date time - uncomment to use
/*void setDateTime(){

  byte second =      00; //0-59
  byte minute =      09; //0-59
  byte hour =        13; //0-23
  byte weekDay =     1; //1-7
  byte monthDay =    5; //1-31
  byte month =       5; //1-12
  byte year  =       13; //0-99

  Wire.beginTransmission(DS1307_ADDRESS);
  Wire.write(zero); //stop Oscillator

  Wire.write(decToBcd(second));
  Wire.write(decToBcd(minute));
  Wire.write(decToBcd(hour));
  Wire.write(decToBcd(weekDay));
  Wire.write(decToBcd(monthDay));
  Wire.write(decToBcd(month));
  Wire.write(decToBcd(year));

  Wire.write(zero); //start

  Wire.endTransmission();

}*/
```

Sun Positon (FEB 08 2013) Bay Area Input Data

Starting and Ending at Midnight

Time	**Azimuthal Angle**	**Time**
(Hour)	(Degrees Clockwise from North)	(Seconds)
0.25	0	900
0.5	0	1800
0.75	0	2700
1	0	3600
1.25	0	4500
1.5	0	5400
1.75	0	6300
2	0	7200
2.25	0	8100
2.5	0	9000
2.75	0	9900
3	0	10800
3.25	0	11700
3.5	0	12600
3.75	0	13500
4	0	14400
4.25	0	15300
4.5	0	16200
4.75	0	17100
5	0	18000
5.25	0	18900
5.5	0	19800
5.75	0	20700
6	0	21600
6.25	0	22500
6.5	0	23400
6.75	0	24300
7	107.16	25200
7.25	109.45	26100
7.5	111.78	27000
7.75	114.17	27900
8	116.64	28800
8.25	119.18	29700
8.5	121.82	30600
8.75	124.56	31500

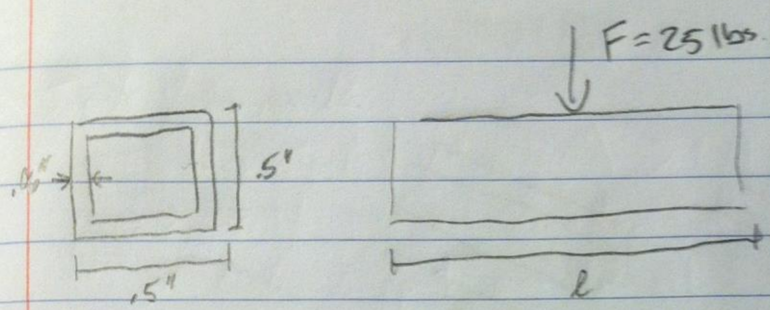
9	127.41	32400
9.25	130.39	33300
9.5	133.5	34200
9.75	136.75	35100
10	140.16	36000
10.25	143.72	36900
10.5	147.44	37800
10.75	151.32	38700
11	155.35	39600
11.25	159.53	40500
11.5	163.83	41400
11.75	168.24	42300
12	172.74	43200
12.25	177.29	44100
12.5	181.86	45000
12.75	186.42	45900
13	190.93	46800
13.25	195.36	47700
13.5	199.69	48600
13.75	203.9	49500
14	207.96	50400
14.25	211.87	51300
14.5	215.63	52200
14.75	219.23	53100
15	222.66	54000
15.25	225.95	54900
15.5	229.09	55800
15.75	232.1	56700
16	234.98	57600
16.25	237.75	58500
16.5	240.41	59400
16.75	242.98	60300
17	245.46	61200
17.25	247.87	62100
17.5	250.22	63000
17.75	252.52	63900
18	0	64800
18.25	0	65700
18.5	0	66600

18.75	0	67500
19	0	68400
19.25	0	69300
19.5	0	70200
19.75	0	71100
20	0	72000
20.25	0	72900
20.5	0	73800
20.75	0	74700
21	0	75600
21.25	0	76500
21.5	0	77400
21.75	0	78300
22	0	79200
22.25	0	80100
22.5	0	81000
22.75	0	81900
23	0	82800
23.25	0	83700
23.5	0	84600
23.75	0	85500
24	0	86400

Appendix A.17: Hand Calculations

See attached sheets for referenced calculations in the listed order. Supplemental calculations and development of design can be found in sketches and notes taken in each team members project notebook.

2/14/13



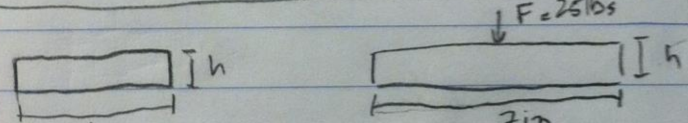
$$I_x = b_o^4/12 - b_1^4/12 = \frac{b_o^4 - b_1^4}{12} = \frac{.5^4 - .44^4}{12} = \frac{.0625 - .03748}{12}$$

$$= .002085 \text{ in}^4$$

$$\sigma = \frac{yFl}{4I} = \frac{.25(25)\,l}{4(.002085)} = 750\,l$$

yield strength = 46,000 psi ⇒ w/ s.f. of 2 ⇒ 23,000

$$l = \frac{23{,}000}{750} = \boxed{30''}$$



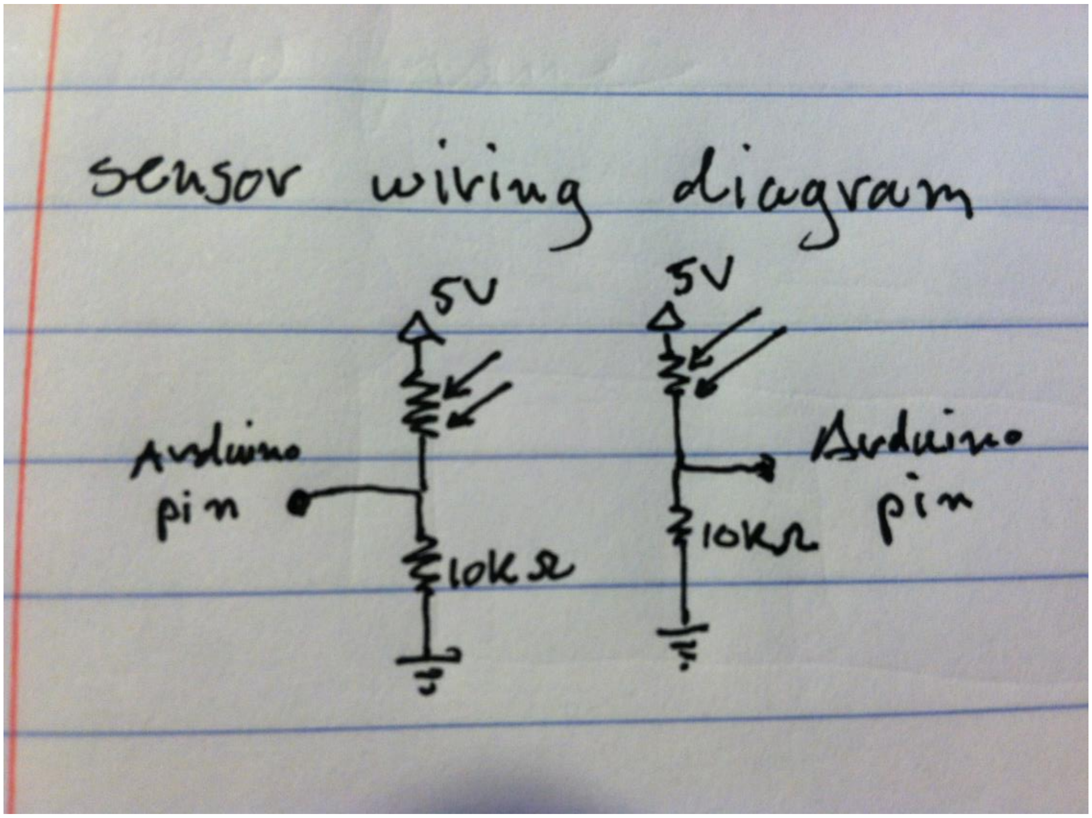
$$I_x = bh^3/12 = \frac{4h^3}{12} = \tfrac{1}{3}h^3$$

$$\sigma = \frac{yFl}{4I} = \frac{\frac{1}{2}h(25)(7)}{4\,\frac{1}{3}h^3} \Rightarrow \sigma h^2 = \tfrac{3}{4}\tfrac{1}{2}(25)(7)$$

$$h^2 = 65.625\,\frac{1}{\sigma} \Rightarrow \sigma = 35{,}000/2 = 17500 \text{ psi}$$

$$h = \sqrt{\frac{65.625}{17500}} = \boxed{.0612''}$$ change from .5" – .25"

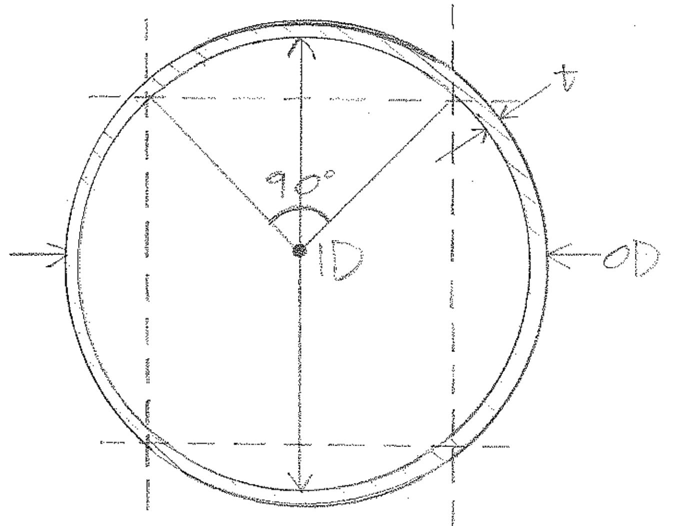
(still need to consider concentrations)


sensor wiring diagram
5V
Arduino
pin
10kΩ
5V
Arduino
pin
10kΩ

OCT. 1, 2012

PVC OPTIMIZATION

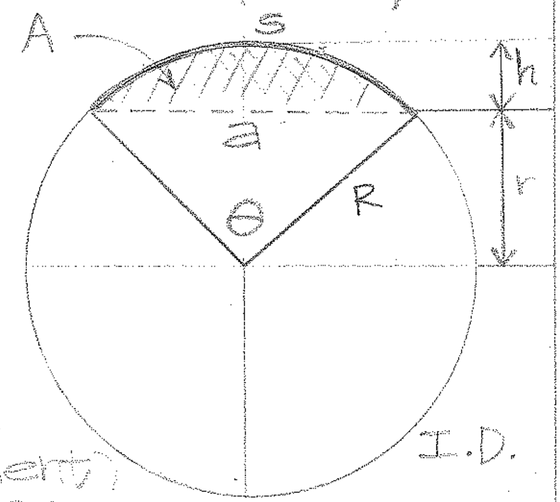
DIVISIONS OF 4 PER TUBE



$C = 2\pi R = \pi D$

ONE CRESCENT SHAPE

$= C/4 = \pi D/4$



Reference: www.Professional-plastics.com (see attachment)

Nominal PIPE SIZE	O.D.	average I.D.
4"	4.500"	3.998"

* We will use inner diameter as initial measurements to calculate volume and amount of wax required for each louver.

* The outer diameter measurements will be used to calculate the overall size of each louver for integration within an assembly.

$A = \text{area}_{\text{sector}} - a_{\text{isosceles triangle}}$

$A = \frac{1}{2} R^2(\theta - \sin\theta)$

$R = h + r$

$s = R\theta$

$r = R\cos(\frac{1}{2}\theta)$

$r = \frac{1}{2} a\cot(\frac{1}{2}\theta)$

$r = \frac{1}{2}\sqrt{4R^2 - a^2}$

CHORD

$a = 2R\sin(\frac{1}{2}\theta)$

$a = 2r\tan(\frac{1}{2}\theta)$

$a = 2\sqrt{R^2 - r^2}$

$a = 2\sqrt{h(2R - h)}$

ANGLE

$\theta = s/R$

$\theta = 2\cos^{-1}(r/R)$

$\theta = 2\tan^{-1}(a/2r)$

$\theta = 2\sin^{-1}(a/2R)$

Reference: mathworld.wolfram.com (see attachment)

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R = 2 INCHES

h	$r = R - h$	$a = 2\sqrt{R^2 - r^2}$
0.4"	1.6"	2.40"
0.6"	1.4"	2.86"
0.8"	1.2"	3.20"
1.0"	1.0"	3.46"
1.2"	0.8"	3.66"
1.4"	0.6"	3.82"
1.6"	0.4"	3.919"
1.8"	0.2"	3.98"

See Excel attachment for all PVC options.

$\theta = 2\cos^{-1}(r/R)$ $s = R\theta$

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Nom. PIPE SIZE : 4"

$R_{ID} = I.D./2 = 1.999"$

$\theta = 360°/4 = 90° \cdot \frac{\pi}{180°} = 1.57 \text{ radians} = \frac{\pi}{2} \text{ rads}$

$S_{ID} = \theta R = \frac{\pi}{2}(1.999") = 3.140"$

$r_{ID} = R\cos\left(\frac{1}{2}\theta\right) = (1.999")\cos\left(\frac{1}{2}\cdot\frac{\pi}{2}\right) = 1.414"$

$h_{ID} = R - r = 1.999 - 1.414 = 0.585"$

$a_{ID} = 2\sqrt{(1.999)^2 - (1.414)^2} = 2.826"$

$A_{ID} = \frac{1}{2}R^2(\theta - \sin\theta) = \frac{1}{2}(1.999)^2\left(\frac{\pi}{2} - \sin\frac{\pi}{2}\right)$

$A_{ID} = 1.145 \text{ in}^2$

To cover 3' by 7' window, proposed length of each louver within the assembly will be approximately 36" for blinds running horizontally across window.

Volume = A_{ID} × Length

$V_{ID} = 1.145(36) = 41.203 \text{ in}^3$

(see Excel attachment for all PVC options)

From attachment...

outer Diameter Dimensions for 4" PVC:

$R_{OD} = 2.25"$

$S_{OD} = 3.535"$

$r_{OD} = 1.591"$

$h_{OD} = 0.659"$

$a_{OD} = 3.182"$

$A_{OD} = 1.445 \text{ in}^2$

$V_{OD} = 52.032 \text{ in}^3$

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INCREASING $\underline{h}$ OR DECREASING $\underline{r}$

$A = \text{area}_{\text{sector}} - \text{area}_{\text{isosceles triangle}}$

$A = \frac{1}{2} R^2 (\theta - \sin\theta)$

$R \rightarrow$ varies with Nominal Pipe size (USE INNER DIAMETER FOR area calculations that wax will take up.)

$\theta = 2\cos^{-1}(r/R)$ * to FIND area

$a = 2\sqrt{R^2 - r^2}$ * to FIND how many louvers req'd to cover window (USE OUTER radius)

Want coverage of entire window for shading of house during the day. So, rather than rounding down for spacing of louvers we will round up for number of required louvers. The excess louvers can hang below the window.

But, since we may have some louver surface area hanging over the window with no solar interaction we will round down for available energy of all louvers.

Blackbody surface area (INNER)

$r_{INNER} \cdot (\text{height or width})$

Reflective surface area (INNER)

$s_{INNER} \cdot (\text{height or width})$
where s is arc length and defined by

$s = R\theta_{INNER}$

OCT. 1, 2012

available PCM Mass

$V_{total} \cdot \rho_{liquid}$

* Density as liquid b/c that is when the PCM will take the entire surface area. Expands 10% from solid to liquid!

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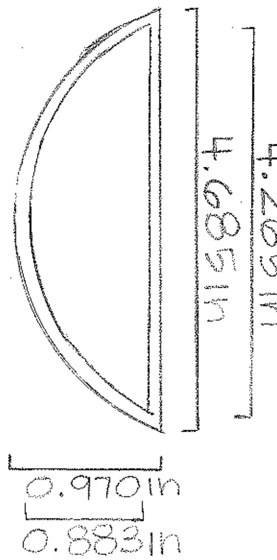
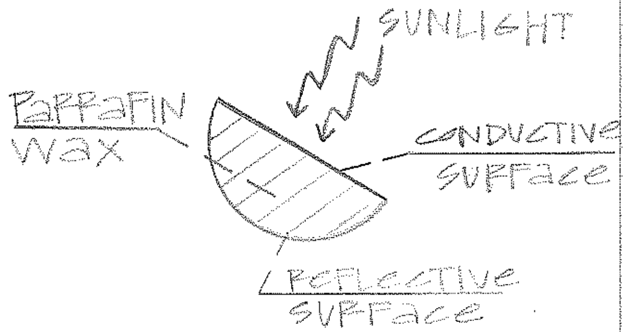
PROPOSED PROJECT DEVELOPMENT: CRESCENT-SHAPED LOUVERS

UTILIZE 6" PVC (see optimization calcs)





$V_{ID} = 93.460\ in^3$

*If liquid wax is originally placed in louver (to avoid ~10% expansion that occurs via phase change), then only ~85% of the louver will be filled with solid wax. We will utilize the entire inner volume to fill with liquid wax.

Louver Energy ABSORPTION / STORAGE
*No losses considered.

$$\underbrace{\left[93.460\,\cancel{in^3}\right]}_{V_{ID}} \cdot \left[\frac{16.387\,\cancel{cm^3}}{1\,\cancel{in^3}}\right] \cdot \underbrace{\left[\frac{0.782\,\cancel{g}}{\cancel{cm^3}}\right]}_{\rho_{liquid}} \cdot \underbrace{\left[\frac{180\,J}{\cancel{g}}\right]}_{h_{sl}}$$

= 215.027 kJ of available energy per louver

To cover 7 foot direction of window.
approx. 17 total horizontal louvers for coverage of (17)(4.685) = inches of the (7)(12") = 84 inches of window. Spacing left for function of assembly between each louver.

$$\left[\frac{215.027\ kJ}{louver}\right] \cdot \left[17\ \cancel{louvers}\right] = 3655.466\ kJ$$

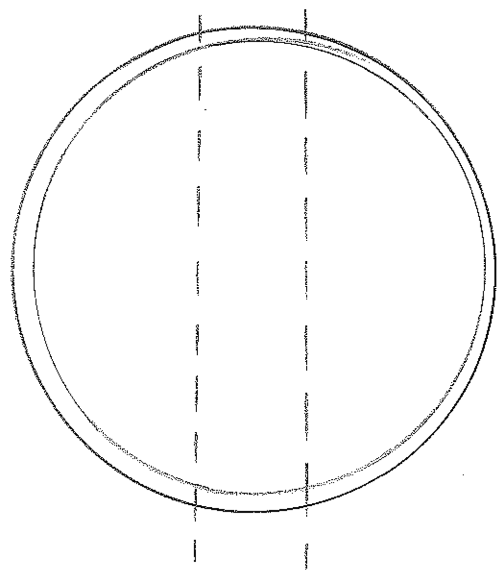
$$\left[3655.466\ \cancel{kJ}\right] \cdot \left[\frac{0.0002778\ kWh}{\cancel{kJ}}\right] = \boxed{1.015\ kWh}$$

for the window

(see Excel attachment for all PVC options)

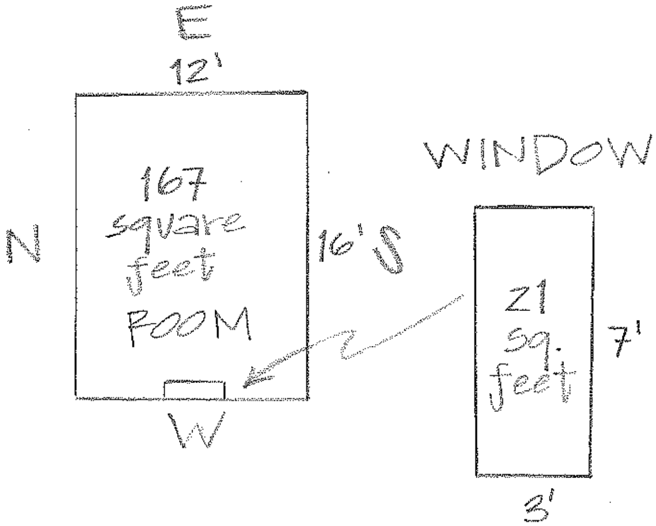
OCT 1. 2012

So, in order to compensate for heat loss in room and potential energy losses due to manufacture and materials chosen for tower, not yet taken into consideration, a larger horizontal shade width must be used or the PVC will have to be used for 2 divisions of blinds rather than 4 to increase volume capacity.



OCT. 1, 2012

Santa Clara's 2013 Solar Decathalon House
BEDROOM includes window facing west



PHASE CHANGE MATERIAL (PCM)
Paraffin Wax Properties

Ideal Wax Melting Temperature
approx. 20-30°C

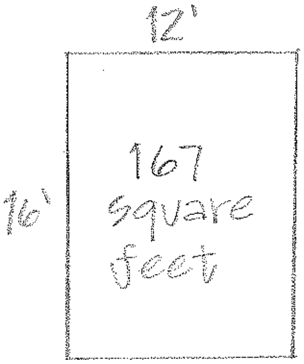
Thermal conductivity
(liquid) $k \cong 0.167$ W/mK
(solid) $k \cong 0.35$ W/mK

Latent Heat of Fusion
*Low-Balling estimate
$h_{sl} \cong 180$ KJ/kg

Density
(liquid) $\rho_l = 0.78$ g/cm³
(solid) $\rho_s = 0.89$ g/cm³

OCT. 1, 2012

Heat Loss of Solar Decathalon Bedroom



assumptions:

R-Values (Transmission Resistances) [BTU per hour]

Floor & Ceiling : R=30
(2x12 Joist ceilings with attic above glass-fiber insulation, and interior 1/2" sheetrock below)

Walls : R=19
(2x4 stud similar walls)

Window : R= ?
(

167 square feet
40 square feet of windows
(see attachment) *See Dec. 1 Calcs revisited.

$$\text{Loss in BTU per hour} = \frac{\text{surface area}}{R} \times \text{temperature difference}$$

$$\text{Infiltration} = \text{cubic ft.} \times R \times \frac{\text{air changes}}{\text{hour}} \times \text{temp. diff.}\ [\Delta T]$$

Need HOURLY!

calculations for each NIGHT hour done using excel sheet "Heat Loss calculator" (see attached).

Heating Load/Losses

*ROOM NEEDS TO BE 72°F!

10 PM	62°F	471 BTUs
11 PM	60°F	565
12 am	58°F	658
1 am	56°F	753
2 am	55°F	800
3 am	56°F	753
4 am	58°F	658
5 am	60°F	565
6 am	62°F	471 BTUs

Total = 6447 BTUs ≅ $\boxed{1.889\ \text{kWh}}$

TOTAL OUTSIDE LOSSES ONLY

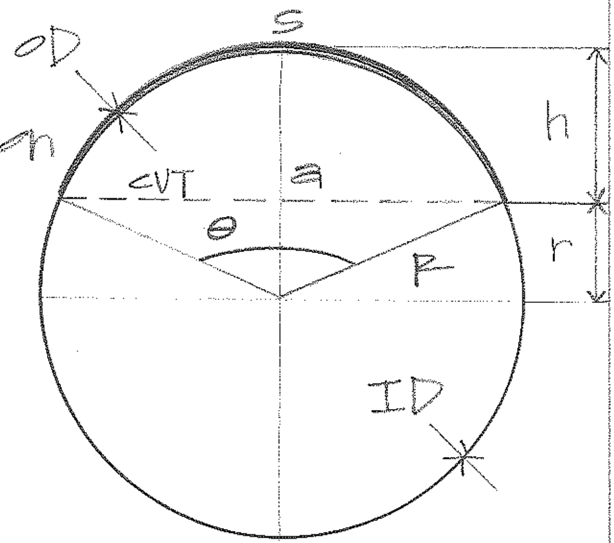
Reference: www.moore.ssae.net/heatloss.html

*Done from 10 pm to 6am, coldest expected time of night at 2am based on averages of previous years. (see attachment) *

NOV. 1, 2012

LOUVER OPTIMIZATION

$s \equiv$ arc length
$a \equiv$ sector length (CUT)
$h \equiv$ height of arced portion
$\theta \equiv$ arc angle
$R \equiv$ radius (INNER)
$r \equiv$ height of triangular portion



$R = h + r$
$s = R\theta$
$r = R\cos(\frac{1}{2}\theta)$
$r = \frac{1}{2}a\cot(\frac{1}{2}\theta)$
$r = \frac{1}{2}\sqrt{4R^2 - a^2}$

CHORD

$a = 2R\sin(\frac{1}{2}\theta)$
$a = 2r\tan(\frac{1}{2}\theta)$
$a = 2\sqrt{R^2 - r^2}$

$a = 2\sqrt{h(2R - h)}$

angle

$\theta = s/R$
$\theta = 2\cos^{-1}(r/R)$
$\theta = 2\tan^{-1}(a/2r)$
$\theta = 2\sin^{-1}(a/2R)$

$A = \frac{1}{2}R^2(\theta - \sin\theta)$

$A = \text{area}_{\text{SECTOR}} - a_{\text{ISOSCELES TRIANGLE}}$

* We will use inner diameter for calculations to estimate volume and amount of wax required to fill each louver.

* OUTER diameter measurements will be used to calculate the size of each louver and overall system for potential assembly.

Reference: mathworld.wolfram.com

NOV. 1, 2012

Starting with a 4" Nominal Pipe size and will integrate other sizes with calculations using Excel or Matlab after completion.

Nominal Pipe size	average outer diameter	average inner diameter
4"	4.500"	3.998"

Take cut increments of 0.1 inches.

h_{inner} (in)	r_{inner} (in)	a_{inner} (in)
0.1	1.899	1.2487
0.2	1.799	1.7431
0.3	1.699	2.1066
0.4	1.599	2.3993
0.5	1.499	2.6450
0.6	1.399	2.8857
0.7	1.299	3.0388
0.8	1.199	3.1990
0.9	1.099	3.3395
1.0	0.999	3.4629
1.1	0.899	3.5710
1.2	0.799	3.6648
1.3	0.699	3.7456
1.4	0.599	3.8143
1.5	0.499	3.8714
1.6	0.399	3.9176
1.7	0.299	3.9530
1.8	0.199	3.9781
1.9	0.099	3.9931
2.0	0.000	3.9980

Reference: www.professionalplastics.com

NOV. 1, 2012

according to excel attachment for chosen 4" inner diameter ABS cut down the center...

veritical blinds
9 blinds required for coverage
8 blinds used to calculate available energy

$V_{ID} = 494.026 \text{ in}^3$ (per louver)

$V_{IDTOT} = 3952.209 \text{ in}^3$ (all louvers)

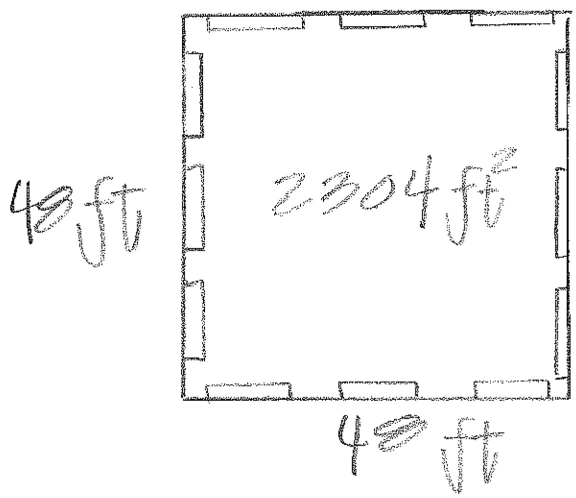
available energy per louver
1136.632 kJ
available energy for entire system
9092.985 kJ
2.526 kWh
total system surface area (inner)
6770.438 in³
available PCM mass
3082.723
total surface area per unit mass
2.196 g/in³

- size chosen b/c
  - aesthetically 6-inches was too large and less available
  - 4 inch provided more available energy than 2-inches
  - cut down the center chosen for ease of manufacturing and any less cause a greater decrease in energy and surface area per unit mass

average home square footage in Western United States in 2010

2386 ft^2 Reference: www.census.gov...

Assume Square Home



Roof ≅ 2304 ft^2

Floor ≅ 2304 ft^2

Exterior Walls ≅ 940.8 ft^2

Windows ≅ 403.2 ft^2

Minimum ceiling Height in Habital Space is 7'-0".

Reference: $4(48)\cdot(7) = 1344\ ft^2$

Windows are allowed to have an area larger than 40% of the gross exterior wall area.

Reference: arch.ced.berkeley...

Assume: 30% of Wall space filled with windows

$1344(30\%) = 403.2\ ft^2$

$1344 - 403.2 = 940.8\ ft^2$

Total Square Footage Surface Area
5952 ft^2

Surface Area Percentage
ROOF = 2304/5952 = 38.71%
FLOOR = 2304/5952 = 38.71%
WALLS = 940.8/5952 = 15.81 %
WINDOWS = 403.2/5952 = 6.77%

Heat Loss Percentage
ROOF = 25%
FLOOR = 15%
WALLS = 35%
WINDOWS = 25%

RATIO

ROOF = 0.646
FLOOR = 0.387
WALLS = 2.214
WINDOWS = 3.693

NOV. 11, 2012

$mass = \pi(2.25^2 - 2.013^2)(72)(0.00144)$
$= 0.3291$ slugs

$I = 0.31987(0.3291)(2.25^2 - 2.013^2)$
$= 0.1080$ slug-in²

$I_{tot} = 0.6 + 0.1080 = 0.7080$ slug-in²
$I_{tot} = 0.7080 / 0.03108 = 22.78$ lb-in²

FOR $\alpha = 1$ rad/s²

$T = 22.78$ lb-in $= 2.573$ N-m

$T = 2.573$ N-m $= 0.00257$ KJ
$T = 0.00257$ KJ $= 7.1 \times 10^{-7}$ kWh
PER LOUVER

SYSTEM PROTOTYPE

$7.1 \times 10^{-7} \underset{\text{LOUVERS}}{(9)} = 6.43 \times 10^{-6}$ kWh
for system
per 1 rad/s²

MAX TURN = 180° = 3.1415 radians

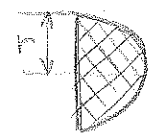
TOTAL SYSTEM ENERGY FOR 180° TURN
$(6.43 \times 10^{-6})(3.1415) = 2.019 \times 10^{-5}$ kWh

(ONE DAY OF OPERATION)

NOV. 11, 2012

CONTROL SYSTEM REQUIRED ENERGY

WAX MASS $= \frac{\pi r^2 L \rho}{2}$ FOR SEMI-CIRCLE



$I_c = 0.31987\, m r^2$

$r = 4.026'' / 2 = 2.013''$

$L = 72''$

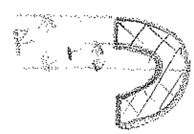
$\rho = 0.9\ g/cm^3 = 0.0325\ lb/in^3$

FROM POUNDS TO SLUGS

$\frac{0.0325\ lb}{in^3} \cdot \frac{0.03108\ slugs}{1\ lb} = 0.00101\ slugs/in^3$

$mass = \frac{\pi (2.013)^2 (72)(0.00101)}{2} = 0.46287\ slugs$

$I_c = 0.31987(0.46287)(2.013)^2 = 0.600\ slug\ in^2$



ABS MASS $= \pi (R^2 - r^2) L \rho$

$I_c = 0.31987\, m (R^2 - r^2)$

$r = 2.013''$

$R = 4.5'' / 2 = 2.25''$

$L = 72''$

$\rho = 1.280\ g/cm^3 = 0.0462\ lb/in^3$

$\frac{0.0462\ lb}{in^3} \cdot \frac{0.03108\ slugs}{1\ lb} = 0.00144\ slugs/in^3$

continued...

Reference: www.stelray.com/density_val.htm

CDR Presentation | Nov. 25, 2012

COMPARISON OF HEATING LOSSES

R-value: The insulating barrier's resistance to heat flow. The higher the number, the more effective the barrier is in reducing heat transfer due to conduction. This reduces heating and cooling costs.

* We want a larger R-value to reduce heat loss, particularly at night, while our system is emitting heat. An increased value reduces conductive heat flow, but does not provide resistance to radiative heat. Radiative heat is what allows our PCM to melt although there is low-E glass and plexi-glass between direct sunlight and the wax.

Reference: www.aps.com_files/services/Res-FAQ/energyefficientwindows.pdf

average R-value for double-pane, clear, low "e" window in wood or vinyl frame type between 2.38 and 2.68.

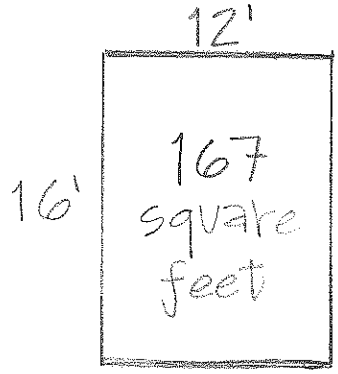
Reference: www.msue.msu.edu

single-pane window ~ R-1

REVISIT OCT. 1 CALCULATIONS AFTER FEEDBACK | Dec. 1, 2012

Santa Clara University's 2013 SD House
BEDROOM with WEST FACING WINDOW
Heat Loss
(During October in Irvine, California)

Reference: www.moorepage.net/heatloss.html



ASSUMPTIONS

R-values (Transmission/ Insulative Resistances)

Floor & ceiling
R = 30 BTU per hour
(2x12 joist ceilings with attic above glass-fiber insulation, and interior 1/2" sheet-rock below)

*alternate assumptions attached

Walls
R = 19 BTU per hour
(2x6 stud walls with glass-fiber insulation, exterior siding, and 1/2" sheet-rock)

INFILTRATION = cubic feet · R · $\frac{\text{air changes}}{\text{hour}}$ · ΔT (temp. difference)

Windows
R = 4
(Triple-Pane, storm-windows)

LOSS IN BTU per hour = $\frac{\text{surface area}}{R}$ · ΔT

Dec. 1, 2012

Calculations for each NIGHT hour done using Excel Sheet Heat Loss Calculator (see attached).

* ROOM NEEDS to be at 72°F at all times!

Heat loss calculated for 9-hour span of Night, from 9PM to 6AM.

Reference: www.weather.com/weather/wxclimatology/daily/92697?climoMonth=10

2012	avg. HIGH	avg. LOW
OCT. 1	71°F	62°F
OCT. 5	71°F	62°F
OCT. 10	70°F	61°F
OCT. 15	70°F	60°F
OCT. 20	70°F	59°F
OCT. 25	70°F	58°F
OCT. 30	69°F	57°F

Reference: www.pgweather.com/archivewx.php?id=KCAIRVIN1&d=20121001

FOR HOURLY TEMPERATURES OCT. 1-2, 15-16, 30-31 averages taken for 2012

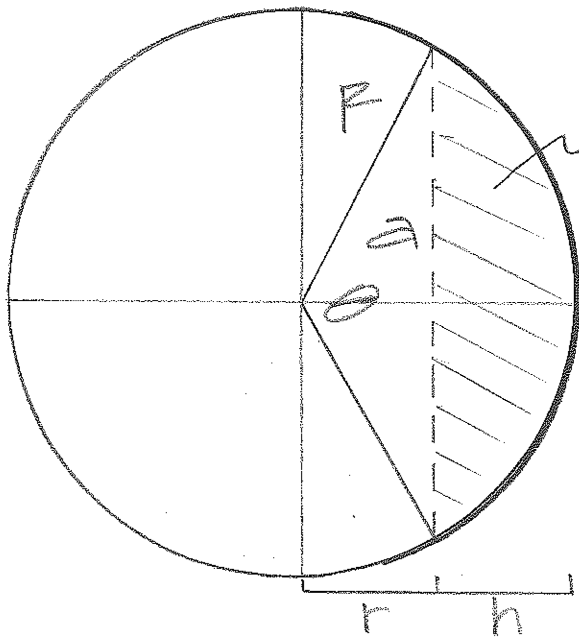
BTUs LOST CALCULATED WITH THOSE averages @ each hour

TOTAL LOSSES = 3917 BTUs

$1 \text{ BTU} = 2.93 \times 10^{-4}$

TOTAL LOSSES = 1.148 kWh

May, 5 2013



$s = R\theta$

$\theta = 2\cos^{-1}(r/R)$

$a = 2\sqrt{R^2 - r^2}$

$A = \frac{1}{2}R^2(\theta - \sin\theta)$

$\theta = 2\sin^{-1}(a/2R)$

Reference: mathworld.wolfram.com

INNER SURFACE AREA

Measured manufactured lowers.

Quarter: $a = 3.625$

Half: $a = 3.875$

Nominal Pipe Size

O.D. 4.500"

I.D. 3.998"

Reference: www.professional-plastics.com

$R = 3.998/2 = 1.999$

$$\theta_Q = 2\sin^{-1}(3.625/3.998) = 130.107^\circ$$

$$\theta_H = 180^\circ$$

$$S_Q = (1.999)(130.107^\circ)(\pi/180^\circ) = 4.54 \text{ in}$$

$$S_H = (1.999)(180^\circ)(\pi/180^\circ) = 6.28 \text{ in}$$

$$SA_{\text{INNER Q}} = sl + al = (4.54)(36) + (3.625)(36) = 293.94 \text{ in}^2$$

$$SA_{\text{INNER H}} = sl + al = (6.28)(36) + (3.875)(36) = 365.58 \text{ in}^2$$

$$A_{\text{INNER Q}} = \tfrac{1}{2}(1.999)^2[130.12^\circ - \sin(130.12^\circ)]\left(\frac{\pi}{180}\right) = 4.51 \text{ in}^2$$

$$A_{\text{INNER H}} = \tfrac{1}{2}(1.999)^2[180^\circ - \sin(180^\circ)]\left(\frac{\pi}{180}\right) = 6.27 \text{ in}^2$$

$$V_{\text{INNER Q}} = (4.51)(36) = 162.36 \text{ in}^3$$

$$V_{\text{INNER H}} = (6.27)(36) = 225.97 \text{ in}^3$$

$$\rho_{\text{liquid RT28HC}} = 0.768 \frac{\text{kg}}{\text{l}} = 0.01258 \frac{\text{kg}}{\text{in}^3}$$

$$h_{sl\,\text{RT28HC}} = 245 \text{ KJ/kg}$$

$$m_Q = (162.36)(0.01258) = 2.042 \text{ kg}$$

$$m_H = (225.97)(0.01258) = 2.843 \text{ kg}$$

Surface Area per Unit Mass

QUARTER

293.94 in^2/2.042 kg =
143.95 in^2/kg

HALF

365.58 in^2/2.843 kg =
128.59 in^2/kg

Available Energy per louver

QUARTER

[VID][ρliquid][hsl]

$[162.36\cancel{in^3}][0.01258\frac{kg}{\cancel{in^3}}][245\frac{kJ}{\cancel{kg}}]$

E = 500.41 kJ

HALF

$[225.97\cancel{in^3}][0.01258\frac{\cancel{kg}}{\cancel{in^3}}][245\frac{kJ}{\cancel{kg}}]$

E = 696.46 kJ

Assume PUTS PCM Blinds in Bedroom Window (4'x7')

(4')(12") = 48"/3.625 = 13.24

Round Down 13 x 2 = 26

36" x 3.625" CHORD LENGTH Blinds

26(500.41 kJ) = 13,010.66 kJ

$[13,010.66 \text{ kJ}][0.0002778 \frac{\text{kWh}}{\text{kJ}}] = 3.614 \text{ kWh}$ per night

3.614 kWh (365 days)(10 years)

$= 13,192.42 \frac{\text{kWh}}{\text{days}}$ (10 years)

= (13,192.42)(15.5 ¢/kWh)

$2,044.82

California Persons per Household
(2007-2011) = 2.91

Reference: quickfacts.census.gov/...

Residential Consumption of
Natural Gas Per Capita in CA
(2009) 13.0 million BTU

Residential Electricity
Consumption in CA
(2010) 2,337 kWh

PG&E Average Bundled Rates
for Residential
(2011) 15.5 ¢/kWh

→ Reference: apps1.eere.energy.gov...
→ Reference: www.cpuc.ca.gov...

Simple Interest Calculator
$800; %.03; 120 Months
→ 28.03 → $828.03

Reference: www.webmath.com...

Residential Energy consumption in CA

13 million BTU → 3810 kWh

2337 + 3810 = 6147 kWh

Windows are 25% of Heat Loss & Gain in Home

Reference: toronto stucco...

(6147 kWh) 25% = 1536.75

Assume 30% Window coverage in average CA Home (2384 ft^2)

Reference : census.gov...

Approx. 15 Windows

1536.75/15 = 102.45 kWh per year saved by covering 1 window

(102.45)(10 years)(15.5 ¢/kWh)

$158.79

10-Year Savings

$2,044.82 + $158.79 = $2203.61

$2203.61 − 828.03 = $1375.58 savings

Average CA Household per capita per year

2337 + 3810 kWh = 6147 kWh

$(6147 \text{ kWh})(2.91 \underset{\text{per house}}{\overset{\text{avg}}{\text{persons}}}) = 17887.77 \text{ kWh}$

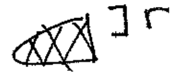
$(17887.77 \text{ kWh})(\$.155/\text{kWh}) = \$2772.6$ per year

$(6147 \text{ kWh})(\$.155/\text{kWh}) = \$952.79$

Control System Required Energy

$\text{wax mass} = \pi r^2 L \rho / 2$

$I_{\substack{\text{semi}\\\text{circle}}} = 0.31987\, m r^2$



$r = 4.026'' / 2 = 2.013''$

$L = 36''$

$\rho = 0.9\ \text{g/cm}^3 = 0.0325\ \text{lb/in}^3$

$\rightarrow 0.00101\ \text{slugs/in}^3$

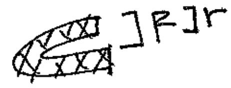
$\text{mass}_{\text{wax}} = \pi (2.013)^2 (36)(0.00101)/2$

$m_{\text{wax}} = 0.2314\ \text{slugs}$

$I_c = 0.31987(0.2314)(2.013)^2 = 0.300\ \text{slug-in}^2$

$\text{ABS mass} = \pi (R^2 - r^2) L \rho / 2$

$I_{sc} = 0.31987\, m (R^2 - r^2)$



$R = 4.5'' / 2 = 2.25''$

$\rho = 1.28\ \text{g/cm}^3 = 0.462\ \text{lb/in}^3$

$\rightarrow 0.00144\ \text{slugs/in}^3$

$\text{mass}_{\text{ABS}} = \pi (2.25^2 - 2.013^2)(36) *$
(0.00144)

$m_{\text{ABS}} = 0.3291\ \text{slugs}$

$I_c = 0.31987(0.3291)(2.25^2 - 2.013^2)$
$= \cancel{0.1080}\ \text{slug-in}^2$
0.054

$I_{total} = 0.300 + \cancel{0.1080} = 0.354$
0.054 slug-in^2

$I_{total} = 0.354/0.0308 = 11.39$ lb-in^2

Assumptions:

α (angular acceleration) $= .1 \frac{rad}{sec^2}$

ω (angular velocity) $= 1 \frac{rad}{sec}$

Motor Torque: $T = I\alpha$

$T = (.1 \frac{rad}{sec^2})(11.39 \text{ lb-in}^2) = 1.139$ lb-in

$T = 0.1287$ N-m $= 0.0001287$ kJ per louver~~s~~

$T = 3.575 \times 10^{-8}$ kWh per louver

$(1.139 \text{ lb-in})(5 \text{ louvers}) = 5.695$ lb-in

$T_{tot} = 5.695$ lb-in $= 0.6435$ N-m

$T_{tot} = 17.875 \times 10^{-8}$ kWh for system per $.1$ rad/sec^2

Max Turn $= 180° = 3.1415$ rad

$(17.875 \times 10^{-8} / .1 \text{ rad/sec}^2)\cancel{(.1 \frac{rad}{sec^2})}(3.1415 \cancel{\text{rad}})$

3.141×10^{-7} kWh

Electrical Power = Mechanical Power

$\rightarrow VI = T\omega$

Motor Voltage, Arduino Voltage, Motor Torque

$$\underbrace{(7.5)}_{\text{Motor Voltage}}\underbrace{(.25)}_{\text{Motor current}} + \underbrace{(5)}_{\text{Arduino Voltage}}\underbrace{(.025)}_{\text{Arduino current}} = \underbrace{(0.6435\,N\text{-}m)}_{\text{Motor Torque}}\omega$$

Motor current, Arduino current

$\rightarrow 1.875 + 0.125 = 0.6435\omega$

$\omega = 3.108$

Motor Provides

$3.108\ \omega,\ 0.6435\ N\text{-}m$

Input Values per system

ARDUINO (MEGA)

RUNS @ 5V, 25mA

SERVO MOTOR

RUNS @ 7.5V, 250mA

$$\frac{kWh}{V} = mAh \longrightarrow \frac{3.141 \times 10^{-7}}{(7.5+5)}$$

$$2.512 \times 10^{-8}\ mAh$$